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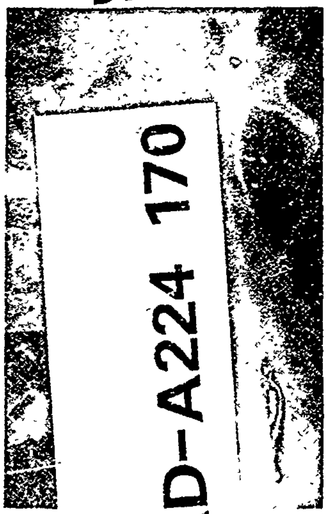

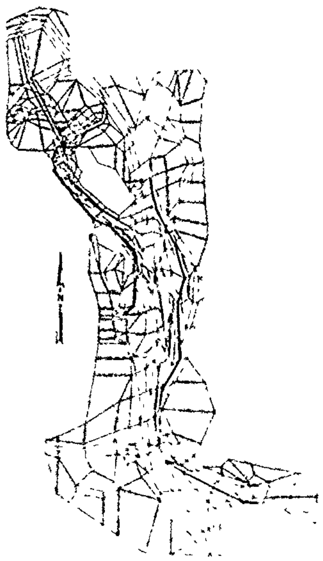

MISCELLANEOUS PAPER HL-90-3

NUMERICAL MODEL PREDICTIONS OF CUMBERLAND SOUND SEDIMENT REDISTRIBUTION ASSOCIATED WITH TRIDENT CHANNEL EXPANSION

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

June 1990
Final Report

Prepared for Department of the Navy
Southern Division
Naval Facilities Engineering Command
Charleston, SC 29411-0068

HYDRAULICS LABORATORY

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Miscellaneous Paper HL-90-3	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Hydraulics Laboratory 6b. OFFICE SYMBOL (If applicable) CEWES-HE-E	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 3909 Halls Ferry Road Vicksburg, MS 39180-6199	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Department of the Navy, Southern Division, Naval Facilities Engineering Command 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) 2155 Eagle Drive PO Box 10068 Charleston, SC 29411-0068	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Numerical Model Predictions of Cumberland Sound Sediment Redistribution Associated with Trident Channel Expansion

12. PERSONAL AUTHOR(S)
Granat, Mitchell A.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ______ TO ______	June 1990	66

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Channel deepening; Channel expansion; Cumberland Sound; Kings Bay (Georgia); Sediment redistribution

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A previously developed modeling system was used to identify potential areas of sedimentation impact or change associated with Trident channel expansion. The modeling system had been designed and verified to predict average currents and long-term average maintenance dredging requirements for the Kings Bay submarine channel. Excellent numerical model to field submarine channel sedimentation verification was previously demonstrated for the pre-Trident condition. The dramatic shoaling impact, a 150 percent increase in required yearly maintenance, predicted by the model for the tested Trident plan channel condition added to the interest in Cumberland Sound sediment redistribution.

Numerical model predictions of long-term average cohesive (clay and silt) and noncohesive (sand and silt) sedimentation (erosion and deposition) patterns within Cumberland Sound are illustrated for pre-Trident and Trident channel conditions. Quantitative assessments should not be attempted for unverified areas; thus, only qualitative

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 — *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. ABSTRACT (Continued).

trend-type comparisons should be made for the unverified areas outside the channel area. In general, subtle sedimentation (erosion and deposition) pattern differences between the two conditions are illustrated. The presented results can be used to identify areas of potential impact for consideration in intensifying field monitoring or in modifying the Kings Bay Coastal and Estuarine Physical Monitoring and Evaluation Program.

The pre-Trident/Kings Bay area was an efficient sediment trap for cohesive sediments. The lengthened, deepened, and widened Kings Bay area was predicted to become an even more efficient sediment trap. Based upon model predictions, the increased cohesive deposition within the improved Trident/Kings Bay area was associated with material the model predicted would have deposited on and adjacent to marsh areas under pre-Trident channel conditions. Relative to the pre-Trident condition, the model predicted that for the Trident channel condition some of the marsh areas could be sites of reduced cohesive deposition.

PREFACE

The modeling study reported herein was a task in a Description of Services (DOS) negotiated in March 1988 between the Department of the Army (DOA), US Army Engineer Division, South Atlantic (SAD), and the Department of the Navy (DON), Naval Facilities Engineering Command (NAVFAC), Southern Division (SOUTHDIV). This task was requested by the Navy's Kings Bay Technical Review Committee (TRC) comprised of representatives from NAVFAC, the National Park Service, the States of Georgia and Florida, and academic consultants. Ms. J. Pope, Chief, Coastal Structures and Evaluation Branch, Coastal Engineering Research Center (CERC), US Army Engineer Waterways Experiment Station (WES), was the Point of Contact (POC) for all WES activities covered by the DOS; Mr. J. Robinson (SAD) was the POC for DOA; and Mr. Darrell Molzan was the POC for SOUTHDIV.

This specific study task was conducted in the WES Hydraulics Laboratory under the general supervision of Messrs. F. A. Herrmann, Jr., Chief of the Hydraulics Laboratory; R. A. Sager, Assistant Chief of the Hydraulics Laboratory; W. H. McAnally, Jr., Chief of the Estuaries Division (ED), Hydraulics Laboratory; and W. D. Martin, Chief of the Estuarine Engineering Branch (EEB), ED. The study was conducted by Mr. M. A. Granat, EEB. Ms. P. H. Hoffman, Math Modeling Group, Waterways Division, HL, assisted in the preparation of the color sedimentation illustrations. This report was prepared by Mr. Granat. Ms. V. Y. Pankow and Mr. R. F. Athow, EEB, performed peer review and provided suggested revisions to the report.

Commander and Director of WES during preparation of this report was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
feet	0.3048	metres
miles (US nautical)	1.852	kilometres
miles (US statute)	1.609344	kilometres
square feet	0.09290304	square metres
square miles (US statute)	2.589988	square kilometres

NUMERICAL MODEL PREDICTIONS OF CUMBERLAND SOUND SEDIMENT REDISTRIBUTION ASSOCIATED WITH TRIDENT CHANNEL EXPANSION

PART I: INTRODUCTION

Background

1. St. Marys Entrance, at the border between Florida and Georgia, is a Federally maintained entrance channel to the Intracoastal Waterway, ports at Fernandina, FL, and St. Marys, GA, and the US Naval Submarine Base at Kings Bay (Figure 1). In the early 1980's, Kings Bay was selected as the Navy's home port for Trident-class submarines. In upgrading the Kings Bay base from the smaller Poseidon-class submarines it was necessary to deepen and widen the interior channels in Cumberland Sound, and deepen, widen, and lengthen the entrance channel through St. Mary's Inlet and in Kings Bay.

2. St. Marys Entrance is a tidal inlet separating Cumberland Island, Georgia and Amelia Island, Florida. Specifically, St. Marys Entrance is located on the Florida-Georgia state line at the coordinates, 30°43′ N and 81°26′ W. The inlet is about 30 miles* north-northeast of Jacksonville, FL, and about 30 miles south of Brunswick, GA. St. Marys Entrance connects Cumberland Sound and the St. Marys River with the Atlantic Ocean.

3. In the past, St. Marys Entrance served as a navigation route to the Atlantic Ocean for boats harbored at Fernandina on the Amelia River and St. Marys on St. Marys River. However, since development of the Kings Bay Naval Submarine Support Base in 1979, the inlet also has been used by submarines and other large vessels. Many public and private interests are located in the study area, including Cumberland Island National Seashore on Cumberland Island, Kings Bay Naval Submarine Base adjacent to Cumberland Sound, Fort Clinch State Park on Amelia Island, and many private land owners on Amelia Island.

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* A table of factors for converting non-SI to SI (metric) units is presented on page 3.

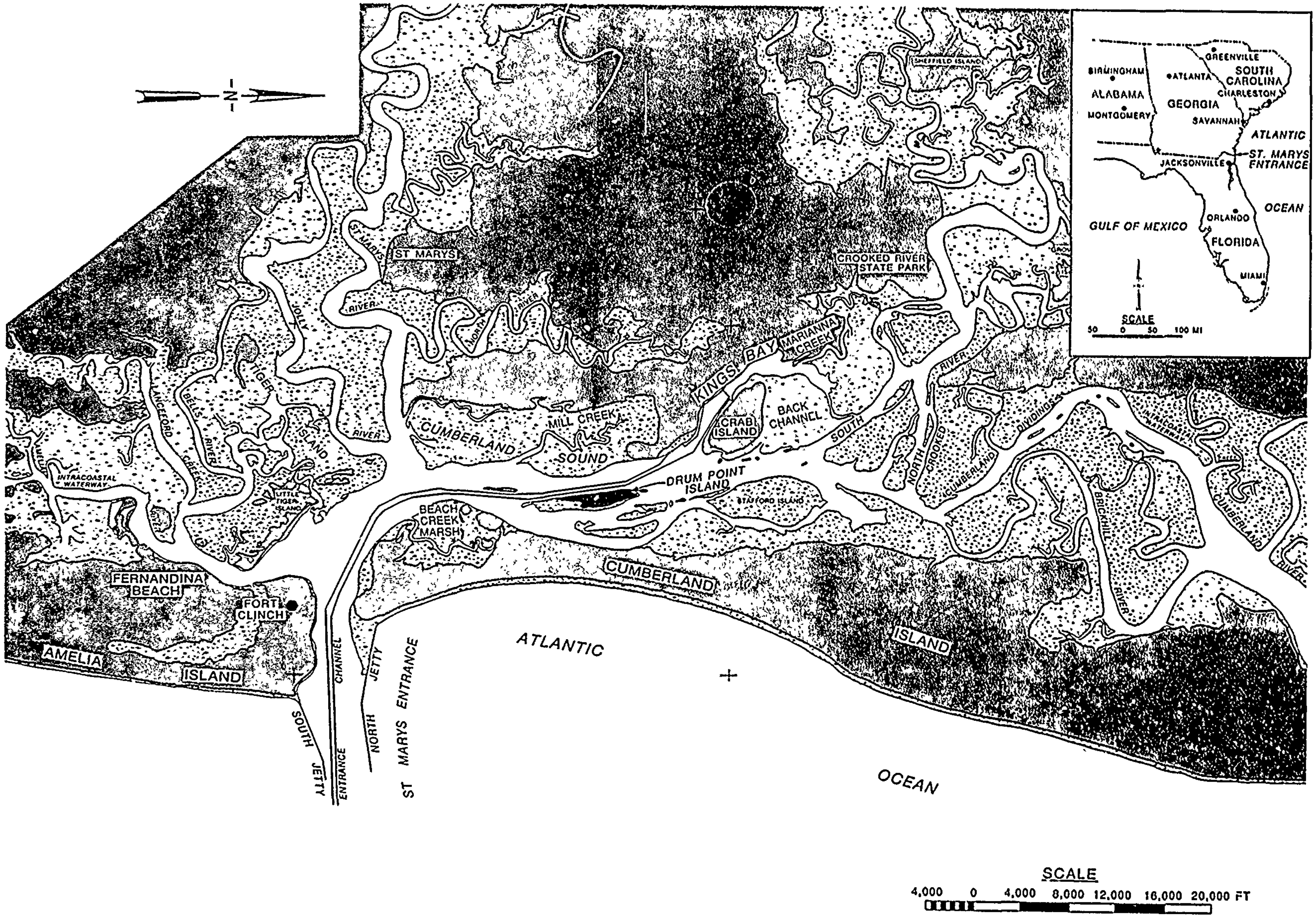

Figure 1. General study area location map

The Cumberland Sound Estuarine System

4. Cumberland Sound, with its extensive salt marsh and sand flat areas, can be classified as a Sea Island estuarine system of southeast Georgia (Figure 1). The mean tidal range at the St. Marys Inlet ocean entrance between Amelia Island, in the State of Florida, and Cumberland Island, in the State of Georgia is 5.8 ft. Maximum spring tidal ranges can exceed 8.0 ft in the interior portions of the estuary. St. Marys Inlet may be considered a narrow-mouth inlet since it is only about 3,000 ft wide at the inlet throat.

5. The primary source of fresh water for the Cumberland Sound estuarine system is the St. Marys River. The river originates in the Okefenokee Swamp, approximately 140 statute miles upstream from Cumberland Sound. The St. Marys drainage basin includes about 1,500 square miles of swampland and coastal plain. The long-term average freshwater discharge at the mouth of the river is about 1,500 cfs. Freshet discharges as high as 18,000 cfs have been recorded. Suspended sediment concentrations within the St. Marys River are generally low.

6. The Crooked River, located approximately 7.5 nautical miles north of the St. Marys River, is the second largest contributor of fresh water to the Cumberland Sound system. This river is much smaller than the St. Marys and consists of a drainage basin of about 90 square miles. The average Crooked River discharge is about 100 cfs. The total fresh water entering Cumberland Sound from the remaining drainage basins is estimated to be less than the Crooked River flow.

7. Cumberland Sound encompasses part of the Atlantic Intracoastal Waterway (AIWW) system. It is connected to St. Andrew Sound, to the north, through a series of small river and creek channels and extensive marsh areas. St. Andrew Inlet is more than four times as wide as St. Marys Inlet. Tidal exchange occurs between Cumberland Sound and St. Andrew Sound. To the south, Cumberland Sound connects to Nassau Sound through small river and creek channels and marsh areas. Little to no tidal exchange is thought to occur between Cumberland Sound and Nassau Sound. National Ocean Survey (NOS) charts 11488 and 11502, respectively, illustrate the northeast Florida and southeast Georgia coastlines and estuarine systems.

8. The relatively low average total freshwater discharge into Cumberland Sound and high tidal range and associated strong tidal currents generally

maintain the sound as a well-mixed estuarine system. Salinity within the sound is generally vertically and laterally homogeneous. Longitudinally, salinity within the sound is only slightly reduced from the ocean entrance conditions. Salinity typically varies from about 26 to 32 ppt during the year.

9. A distinct difference between Cumberland Sound and other southeast Georgia estuarine systems is the deep-draft channel leading into the Naval Submarine Base, Kings Bay. Kings Bay, an embayment located adjacent to and west of Cumberland Sound, is about 5.5 nautical miles north of St. Marys River and about 2 nautical miles south of Crooked River. Kings Bay was developed in the late 1950's as an emergency Army Munitions Operation Transportation facility. Channel depths were authorized at 32 ft mean low water (mlw);* however, the facility was never placed into operational use and was in a standby mobilization status with channel depths of about 32 ft maintained on an "as time and money permitted" basis.

10. As indicated in an Environmental Impact Statement prepared in June 1976 for a one-time maintenance dredging operation, approximately 1.7 million cubic yards of material were removed from the turning basin and Kings Bay channel area. The last previous maintenance dredging took place in 1970. Dredging records from this period are limited or not available and cannot be used to assess annual shoaling rates.

11. In July 1978, ownership of the Kings Bay facility was transferred to the Department of the Navy for use as a Naval submarine base for Poseidon class submarines. Between July 1978 and July 1979, approximately 8.6 million cubic yards of material were removed for facility expansion. Major channel realignment, channel widening, and channel deepening were performed. As indicated on the NOS charts, the lower entrance channel project depth varied between 38 to 40 ft with a width of 400 ft. The remaining interior approach channel project depth was 34 ft at a width of 300 ft. Kings Bay had a project depth of 37 ft. According to US Army Engineer District, Savannah, records, maintenance dredging for the Poseidon channel was performed to 39 ft below mlw with 2 additional ft for allowable overdepth.

12. The total length of the interior Poseidon channel, from the throat

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* All depths and elevations described in this report refer to local mean low water which is 2.75 ft below National Geodetic Vertical Datum (NGVD).

of St. Marys entrance adjacent to Fort Clinch to the end of the main docking facility, was about 7 nautical miles. The narrowest point between land masses within Kings Bay was about 1,000 ft and occurred at the entrance to the submarine base. The dredged channel width widened from about 650 ft at the entrance to about 1,200 ft at the downstream end of the main docking facility. At this location, a 643-ft-long Poseidon support tender was usually anchored perpendicular to the channel. A floating dry dock was located about 0.5 nautical miles downstream from the Kings Bay entrance.

13. Between 1982 and 1988 additional Kings Bay submarine channel expansion was undertaken to accommodate Trident class submarines. The ocean entrance channel was deepened to 49 ft with 2 additional ft for allowable overdepth and widened to 500 ft. This channel extended about 12 nautical miles into the Atlantic Ocean. St. Marys Inlet turning and sediment basins were also developed.

14. The interior approach channel project depth was deepened between 44 to 46 ft with 2 additional ft for allowable overdepth and generally widened to 500 ft (with some additional widening at selected areas). Kings Bay project depth was deepened to 47 ft with 2 additional ft for allowable overdepth, widened, and extended another nautical mile to the northwest including an upper turning basin, a Trident dry dock, a small boat facility, and other support facilities. The Poseidon tender was relocated from perpendicular to the channel at Kings Bay to parallel to the channel above the floating dry dock. A lower Kings Bay turning basin was developed in the vicinity of the old tender location, widening Kings Bay to the north. A 41-ft-deep Poseidon waterfront docking area was developed to the west of the floating dry dock and the new tender support area, widening Kings Bay to the west. Approximately 25.5 million cubic yards of material were removed to accomplish the interior Trident channel expansion.

15. A hybrid modeling system (coupled physical and numerical models) was developed for Officer in Charge of Construction (OICC), Kings Bay, to predict average currents and long-term average maintenance dredging requirements for enlarged channel and port facilities. Verification and pre-Trident (base) and Trident (plan) channel results from this modeling system are presented in detail in two separate reports (Granat et al. 1989 and Granat and Brogdon, in preparation).

Objective

16. The objective of the present task is to identify potential sediment sources and sediment redistribution associated with the Trident channel expansion.

Approach

17. As requested by the Navy's Kings Bay Technical Review Committee (TRC), the approach taken was to use the available and previously verified models to identify potential areas of predicted sedimentation (erosion or deposition) impact or change for consideration in modifying the proposed five-year Kings Bay Coastal and Estuarine Physical Monitoring and Evaluation Program. This approach was limited to an in-depth analysis of previous sediment model results and has several underlying qualifications associated with it.

18. Provisions. The hybrid modeling system has been verified to reproduce submarine channel sedimentation for the pre-Trident condition. The system has not been verified for areas outside of the channel prism and such verification cannot be accomplished with existing field data. The models were designed using the most recent survey information available. Channel information was obtained from 1982 (and later) examination surveys. Information for areas outside of the channel prism were obtained from the 1983 NOS bathymetric charts. In some instances, the presented information date back to data collected in 1934-1935. It is stressed that the developed modeling procedures, including the wetting and drying algorithm and the marsh schematization, the mean average tide and freshwater discharge conditions, and the long-term extrapolation, are approximations to complex hydrodynamic and sedimentation processes. The developed modeling procedures were the most advanced available at the time the work was performed, but were simple compared to the natural estuarine system and its dynamic processes.

19. Given the funding and the time constraints, this approach of extending the present model to address questions outside of the main submarine channel can be justified as the best means available for identifying potential areas of impact for intensive field monitoring purposes. Analyses need to be carefully considered when interpreting results from unverified areas of the

model. Only general qualitative, trend-type comparisons and assessments should be performed; quantitative assessments should not be performed for the unverified areas. In addition to the required modeling simplifications, assumptions, and approximations which can be arguably justified as desirable or necessary, the actual constructed Trident channel differed from the Trident channel tested in the models. Small depth differences between the actual constructed Trident channel and the requested channel depths tested in the models are described in Part III of this report. In addition, the lower St. Marys Inlet turning and sediment basins and the lower Kings Bay turning basin were designed subsequent to model testing and, therefore, were not included in the model study. The Trident channel model testing condition also included a proposed rerouting of the AIWW from the submarine channel, on the west side of Drum Point Island, to the east side of Drum Point Island; therefore, the modeled plan condition included a 150-ft-wide, 12-ft-deep channel to the east of Drum Point Island. The AIWW has not been rerouted in the field.

PART II: DESCRIPTION OF THE MODELS

The Physical Model

20. The Kings Bay physical model was a distorted-scale fixed-bed concrete model that reproduced approximately 206 square miles of southeast Georgia and northeast Florida, and about 220 square miles of the adjacent Atlantic Ocean. The physical model limits are shown in Figure 2. A complete description of the model and its appurtenances may be found in Granat et al. (1989). The model was constructed to linear scale ratios, model-to-prototype, of 1:100 vertical and 1:1,000 horizontal; the vertical scale in the physical model was stretched 10 times relative to the horizontal scale. This is a typical scaling factor used for estuarine physical models. The Kings Bay physical model was approximately 126 ft long and 108 ft wide and covered an area of about 12,600 sq ft. Salinity in the model was maintained at a 1:1 ratio. The vertical and horizontal scales dictated the other scaling factors (time, velocity, discharge) based on Froudian relationships. Time, for example, was compressed in the physical model so that one complete ebb and flood semidiurnal tidal cycle (12.42 hr) occurred in 7.452 min on the model.

21. The physical model was an accurate scaled reproduction of the Cumberland Sound estuarine system. Verification of the physical model to reproduce observed tide, velocity, and salinity field measurements was undertaken to ensure the reliability of model results. Stainless steel artificial roughness or resistance strips projecting from the molded concrete bed of the model served as the primary means of adjusting the physical model to reproduce hydrodynamic field conditions. A complete documentation of the physical model verification is provided in the verification report (Granat et al. 1989).

22. Briefly, two distinct physical model verification efforts were undertaken. The first effort centered around the pre-Trident channel conditions and field data sets collected on 10 and 12 November 1982 and focused on the areas in and south of Kings Bay. This field data collection effort, although conceived as a supplement to the US Geological Survey's data collected during November 1981 and July 1982, became the primary data set for physical model verification. The physical model was found to reasonably reproduce the pre-Trident channel field measurements.

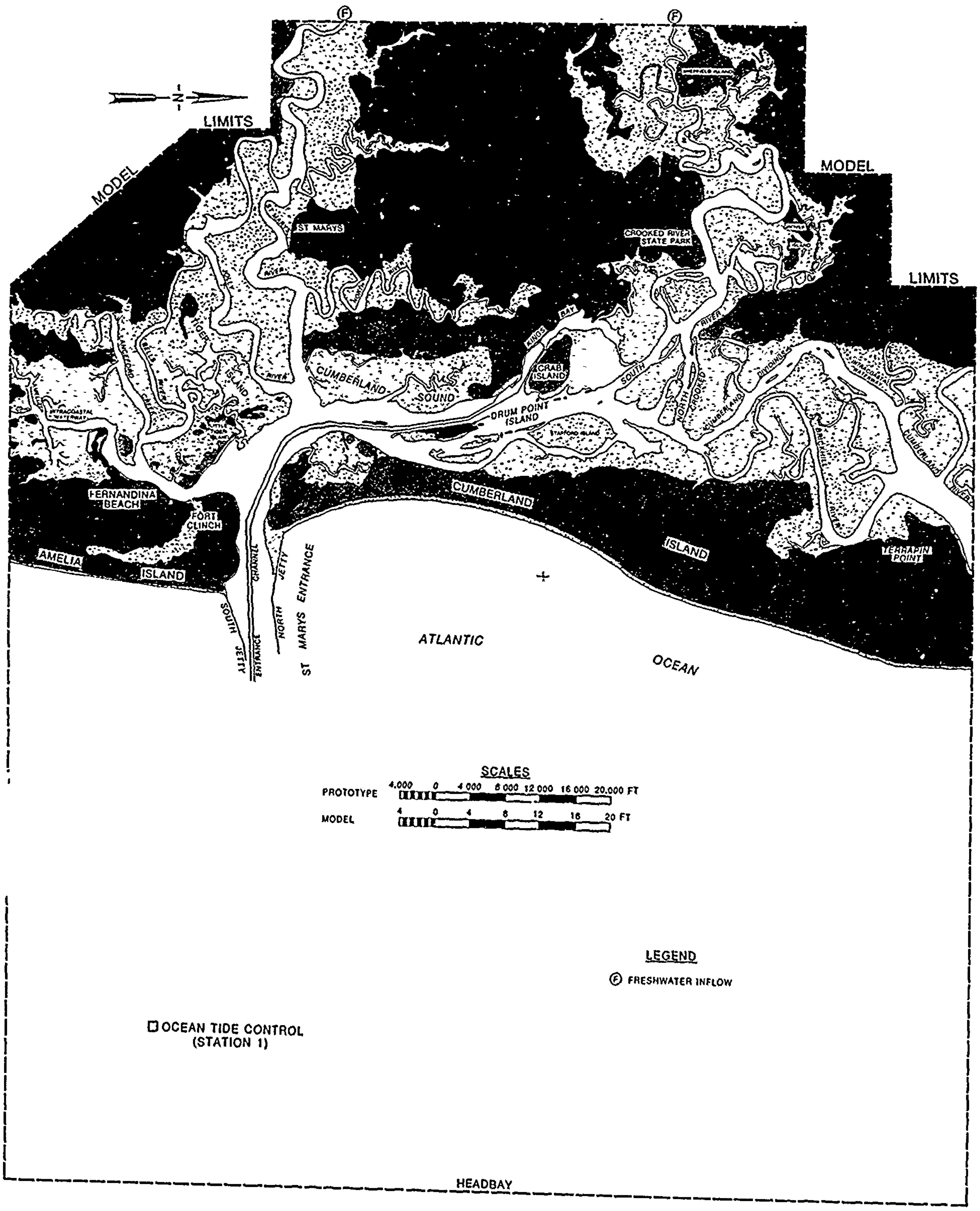


Figure 2. Physical model limits

23. The second physical model verification effort centered around the field data set collected on 26 January 1985 and focused on the areas in and north of Kings Bay. This data set was collected during a transitional channel condition with the upper end of Kings Bay already dredged to Trident channel depths. This collection effort was undertaken to verify the velocity and tide conditions north of Kings Bay since hybrid model investigations had indicated the importance of flow characteristics in this portion of the system. Additional roughness strip and geometry adjustments were performed in the physical model areas north of Kings Bay prior to final verification to the transitional channel condition. The physical model was found to reasonably reproduce the transitional channel field condition.

24. As verified, the physical model can be used to investigate the three-dimensional flow characteristics of the Cumberland Sound estuarine system associated with the long-term average freshwater discharge and average tidal conditions. The physical model can be used to examine alternative conditions; geometry in the model can be modified physically to represent the desired new condition and the model rerun to assess the resulting three-dimensional flow characteristics. Comparison of results between two model runs with identical conditions except for the plan modification provides a means of assessing potential hydrodynamic impacts associated with the plan modification.

25. Ideally, a new physical model base test (pre-Trident channel condition) should have been conducted following the transitional channel verification; however, the need for expedited testing of the Trident plan channel did not permit the schedule to be adjusted for that purpose. The single, original pre-Trident verification base test was used for subsequent comparison with the plan channel. A complete analysis of base and plan channel hydrodynamic physical model impacts is provided in the pre-Trident and basic Trident channel hybrid model report (Granat and Brogdon, in preparation).

26. A principal task of the physical model was to provide average boundary forcing conditions for the numerical model and to provide an expanded data set for comparisons. Briefly, physical model tidal cycle ocean water levels collected at the St. Marys Inlet entrance were used as the numerical model ocean boundary forcing conditions. Physical model tidal cycle velocity observations collected at the Amelia, Jolly, St. Marys, Crooked, and

Cumberland River locations corresponding to the numerical model boundaries were depth-averaged and used as the numerical model upstream boundary forcing conditions. Physical model tide and velocity measurements were also collected at selected interior locations throughout the modeled area of interest for numerical model verification.

The Numerical Models

27. The numerical modeling system used in this study was the US Army Corps of Engineers Open Channel Flow and Sedimentation--TABS-2 (Thomas and McAnally 1985). TABS-2 is a collection of preprocessor and postprocessor utility codes and three main finite element two-dimensional depth-averaged computational programs. The finite element method provides a means of obtaining an approximate solution to a system of governing equations (i.e., equations of motion) by dividing the area of interest into smaller subareas called elements; time-varying partial differential equations are transformed into finite element form and then solved in a global matrix system for the modeled area of interest. The solution is smooth across each element and continuous over the computational area. A wetting and drying algorithm was used in modeling the extensive marsh and intertidal areas of the estuarine system. Appendix A provides a concise summary of the TABS-2 modeling system.

28. Figure 3 illustrates the finite element mesh (Mesh 4) used during this investigation. This mesh was developed for the upper basin remedial measures testing. The shaded areas highlight those areas that flooded and dried during the tidal cycle. A small mesh revision was required between the pre-Trident base and Trident plan channel schematization for the Poseidon waterfront docking facility to allow proper reproduction of the flooding and drying process. This revision, illustrated in the insets of Figure 3, increased the number of nodes and elements by one for the base condition (i.e., from 1,117 elements and 3,223 nodes for the plan condition to 1,118 elements and 3,224 nodes for the base).

29. A complete documentation of the developed numerical modeling procedures and their verifications may be found in Granat et al. (1989). Briefly, the numerical hydrodynamic code (RMA-2V) used the boundary forcing conditions derived from the physical model to solve the depth-integrated equations of conservation of mass and momentum in two horizontal directions

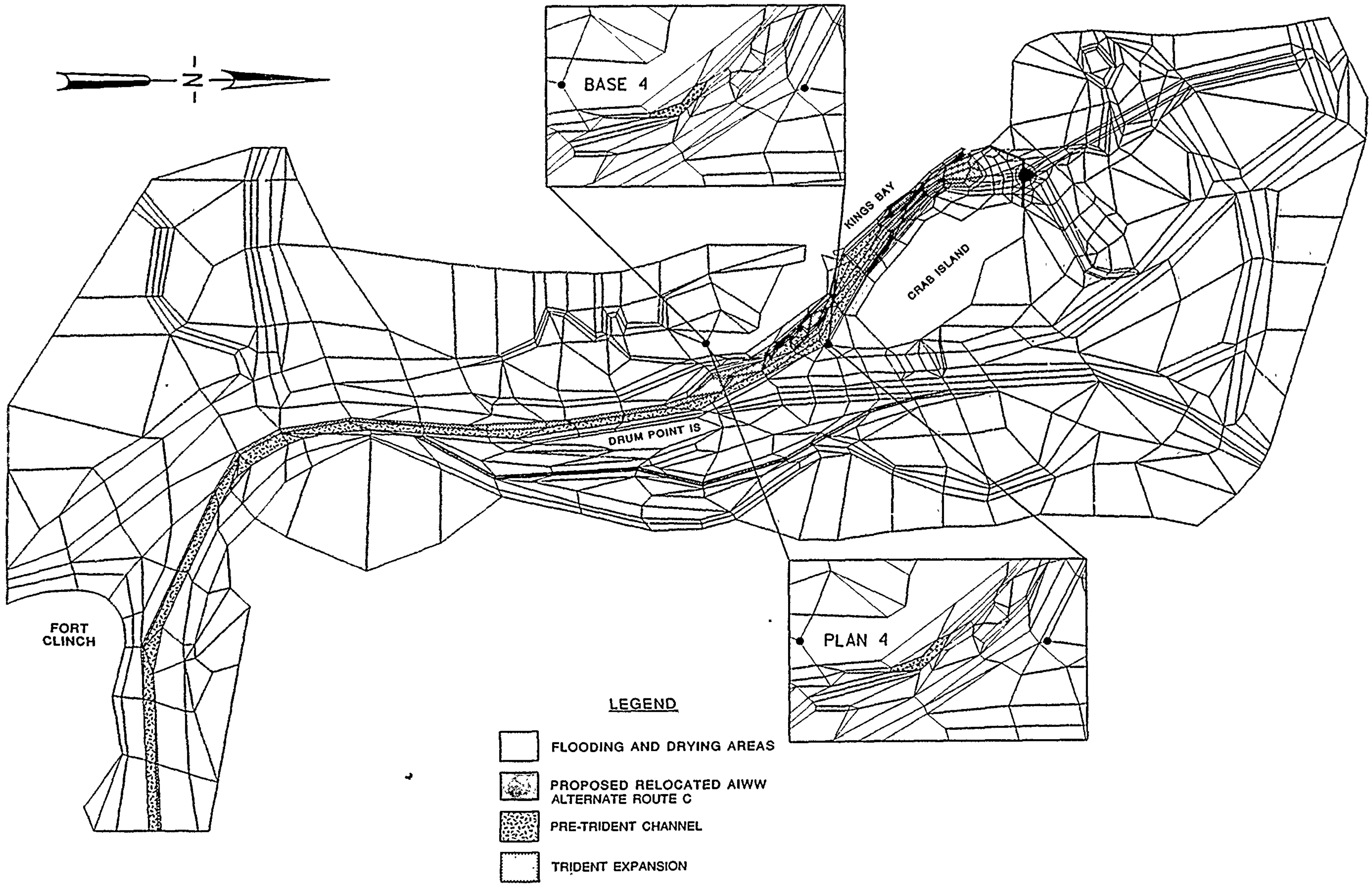


Figure 3. Numerical model Mesh 4

and provided hydrodynamic solutions for water-surface elevations and horizontal velocity components over the entire modeled area of interest. Verification of RMA-2V was accomplished through water-surface elevation and velocity comparisons with corresponding physical model data. Numerical model marsh elevation schematization, and bottom roughness (Manning's n) and eddy viscosity coefficient assignments (Table 1) based on physical characteristics, provided the necessary means for verifying the numerical model.

30. Marsh-estuarine circulation interaction was found to be important in achieving proper reproduction of Cumberland Sound and Kings Bay hydrodynamic characteristics. A compromise between tidal agreement and velocity agreement was made in achieving the desired reproduction between the numerical model and the physical model measurements. A nominal marsh elevation of +4.0 ft was selected in schematizing the numerical model marsh areas that flooded and dried during the tidal cycle. Higher numerical model marsh elevations improved tidal reproduction (higher high water and lower low water elevations) but resulted in overall reduced current velocities. Precise (field) marsh elevations were not known. The +4.0 ft elevation was felt to be a valid average marsh elevation approximation for modeling purposes.

31. An excellent main channel ebb and flood velocity phase and magnitude agreement with the physical model measurements was demonstrated using the developed numerical modeling procedures and assigned coefficients. Tributary and secondary channels adjacent to marsh areas demonstrated excellent velocity phase agreement and a slightly reduced numerical model ebb and flood velocity magnitude, relative to the physical model measurements. Excellent tidal phase and midtide water level agreement was also demonstrated. Numerical model high and low water elevations were generally within 0.1 to 0.3 ft of the physical model measurements for the pre-Trident channel verification conditions (i.e., numerical model tidal range was reduced relative to the physical model). This agreement (and compromise discussed in the above paragraph) was considered acceptable since tidal predictions were not an explicit objective of the modeling effort. An improved numerical model to physical model agreement in tide and velocity characteristics was generally achieved during the transitional channel (1985) verification. The greatest improvements were in areas north of Kings Bay, the area in which additional physical model geometry and roughness adjustments were performed. A finer resolution of the marsh areas and of the wetting and drying process would improve the local comparisons;

however, additional modifications were not attempted due to the excellent agreement of the main channel velocity characteristics, the uncertainties of precise marsh elevations, and the primary goals of the modeling effort (i.e., channel velocity and sedimentation predictions).

32. The hydrodynamic results from RMA-2V were used in the numerical sediment transport code STUDH as input information to solve the depth-integrated convection-diffusion equation for a single sediment constituent. The interaction of the flow (transport) and the bed (sedimentation) was treated in routines that computed source/sink (erosion/deposition) terms over the entire modeled area. Cohesive (clay and silt) and noncohesive (sand and silt) sediments were handled separately. Sediment modeling results provided an average sedimentation (erosion or deposition) approximation across each computational element.

33. Verification of STUDH was accomplished through comparison of model predictions with actual pre-Trident channel field shoaling rates. A pre-Trident channel average shoaling rate of 1.2 million cubic yards per year was determined from suitable hydrographic field surveys collected between July 1979 and August 1982. Seasonal extreme values varied from 0.4 million to 2.6 million cubic yards per year. Relatively low shoaling rates, less than 1.0 ft per year, were indicated for the navigation channel in Cumberland Sound, while high shoaling rates, greater than 3.0 ft per year, were indicated for the channel areas within Kings Bay.

34. Sediment model testing coefficients (Tables 2 and 3) were based upon the latest (1985) field data, laboratory testing analyses, and previous modeling experience, as available. Sediment grain size distribution (Figure 4) was the primary adjustment means for noncohesive sedimentation and bed density was the primary adjustment means for cohesive sedimentation. An in situ bed density measuring field effort conducted at Kings Bay during July 1985 indicated that a dry weight bed density of 300 kg/cu m was an appropriate estimate for cohesive sediment modeling purposes. This density was used during the present investigation. A cohesive sediment concentration of 100 mg/ℓ (Table 2) was used as the boundary inflow sediment concentration at each boundary (including the ocean); the outflow concentration was determined internally in the model. In the same fashion, an inflow sediment concentration of 10 mg/ℓ (Table 3) was used for noncohesive sediments.

35. The pre-Trident RMA-2V verification data set was considered an

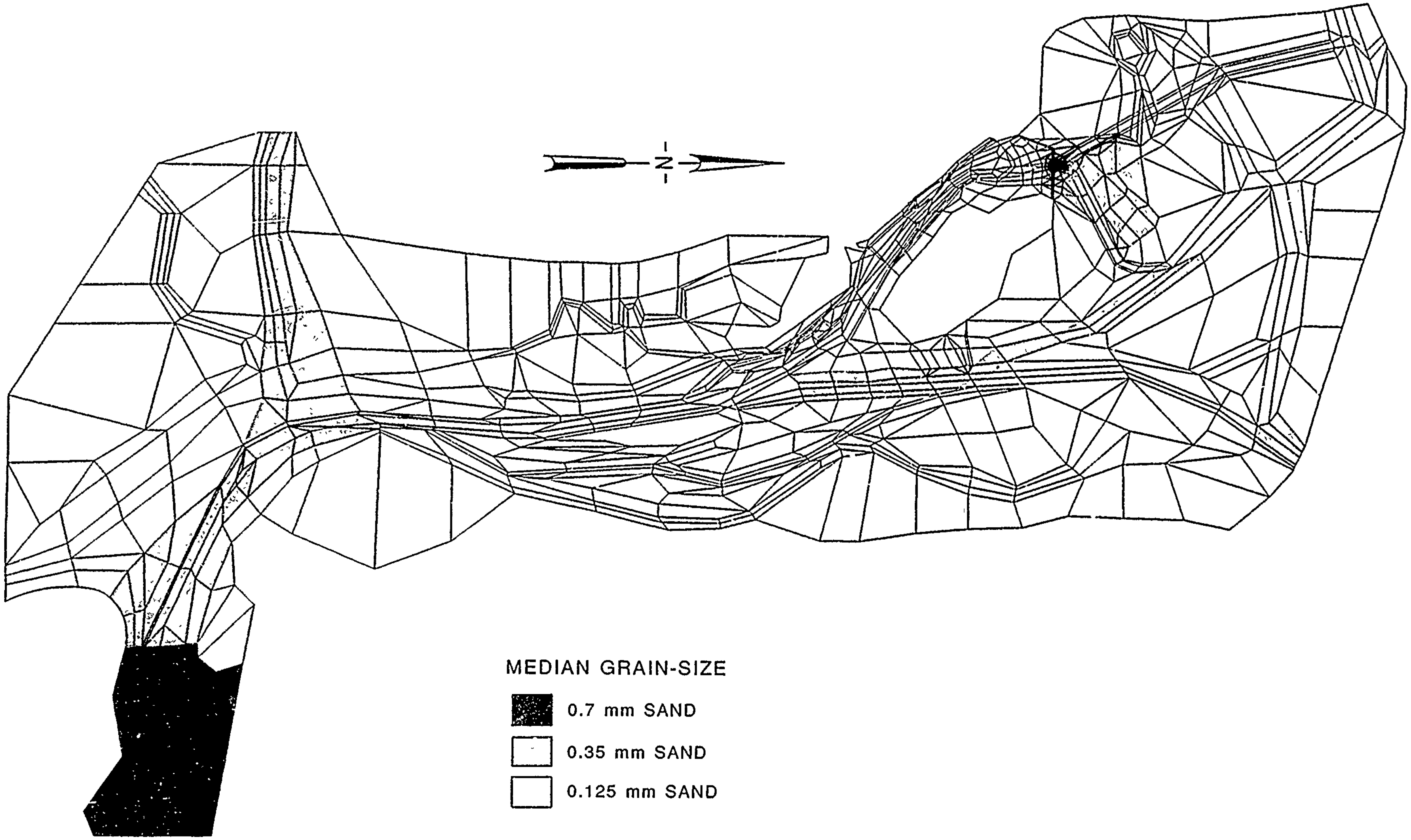


Figure 4. Mesh 4 noncohesive sediment grain size distribution

approximation to the average hydrodynamic conditions associated with the long-term sedimentation processes affecting the navigation channel through Cumberland Sound and Kings Bay. Several cohesive and noncohesive sediment model tidal cycle runs were separately performed using information from previous runs to initialize model sediment concentrations and bed conditions. A complete documentation of the modeling procedure is provided in Granat et al. (1989). Results for each sediment type were then extrapolated to provide model predictions for a complete year of sedimentation. Results for each sediment type were arithmetically combined to produce a yearly sedimentation rate for comparison to the field data. Excellent pre-Trident numerical model to field sediment verification was demonstrated for the channel area using the developed procedures and designated coefficients.

36. A similar modeling procedure and set of model coefficients was used to examine shoaling rates associated with the January 1985 transitional channel geometry conditions. Field shoaling rates were determined for the recently dredged upper Trident turning basin for the January 1985-January 1986 period. This area had no previous survey information for determining a shoaling history. Model predictions for the upper basin area indicated higher deposition rates than the limited field data. Several possible explanations for this difference included low field sediment loads associated with the prolonged east coast drought conditions at that time, the ongoing dredging operations and transitional nature of the channel, and the possible need for further model adjustments. The sediment model was developed and verified for long-term average conditions and additional model adjustments could not be justified based on the limited available data for this area. Additional time and monitoring are required before any other model adjustments can be made with confidence.

Modeling Limitations

37. Any solution method or model is an approximation of the prototype; each possesses its own set of limitations, simplifications, and underlying assumptions. Results obtained from any technique must always be considered as an approximate solution to the given set of conditions. A verification process is usually required to demonstrate the degree of reasonableness for all predictions. The degree of sophistication of the technique and the resulting

verification are offset by time and cost constraints. As in this particular case, adequate field data for the verification process are often very limited or non-existent. As discussed in paragraphs 18 and 19, the only sedimentation field data available for the verification process were for the submarine channel area; quantitative and qualitative model predictions for areas outside of the main channel, therefore, should be viewed cautiously. This is especially true for the marsh areas, where sedimentation and the wetting and drying processes have not previously been verified.

38. Many approximations, simplifications, and assumptions have been made in the developed hybrid approach, and only part of them are explicitly stated in the reports. Each approximation, simplification, and assumption can be arguably justified as necessary or desirable, but the net result must be considered only an approximation to a very complex system and its processes. The developed hybrid method was the most advanced modeling method available to assess submarine channel velocity and sedimentation characteristics. In comparison to the complex interaction of processes within Cumberland Sound, the modeling approach was greatly simplified. The provisions discussed in paragraphs 18 and 19 should also be considered when evaluating the modeling results presented in this report.

PART III: PRE-TRIDENT AND TRIDENT CHANNEL DIFFERENCES

Channel Conditions Tested

39. The pre-Trident channel condition tested in the numerical model reflected the actual channel conditions existing at the time of the November 1982 examination survey. These conditions shall be referred to as base conditions throughout thc remainder of this report. The total area of the maintained 7 nautical mile long interior Poseidon base channel, described in paragraph 11, was 475 acres.

40. The Trident plan channel condition tested in the model reflected the plan channel design requested through January 1985. This testing condition included an ocean entrance channel at a depth of 49 ft and an interior approach channel from the Inlet to the entrance of Kings Bay at a depth of 46 ft. The minimum channel width was 500 ft. Kings Bay was modeled at a depth of 48 ft and the Poseidon waterfront docking and support area was modeled at a 41-ft depth. Figure 5 illustrates the numerical model mesh detail for the base and plan submarine channel conditions tested. The tested plan condition increased the maintained interior channel area to 811 acres, about a 70 percent increase. Approximately 43 percent of the increased channel area was in the high shoaling zones of Kings Bay.

41. The condition tested in the model differed somewhat from the actual as-built channel condition described in paragraphs 13 and 14. In addition to the small depth differences, the model condition did not include the lower Kings Bay turning basin or the St. Marys Inlet turning or sediment basins that were designed subsequent to model testing. The model included the anticipated relocation of the AIWW to an alignment east of Drum Point Island (Figure 3). This relocated channel was modeled as a 12-ft-deep and 150-ft-wide channel. The AIWW was not relocated in the prototype. As documented in two reports (Granat 1987a and b) the impacts of the relocated waterway resulted in subtle localized hydrodynamic and sedimentation changes.

Hydrodynamic Differences

42. A complete description of the predicted hydrodynamic differences between pre-Trident and Trident channel conditions is provided in the hybrid

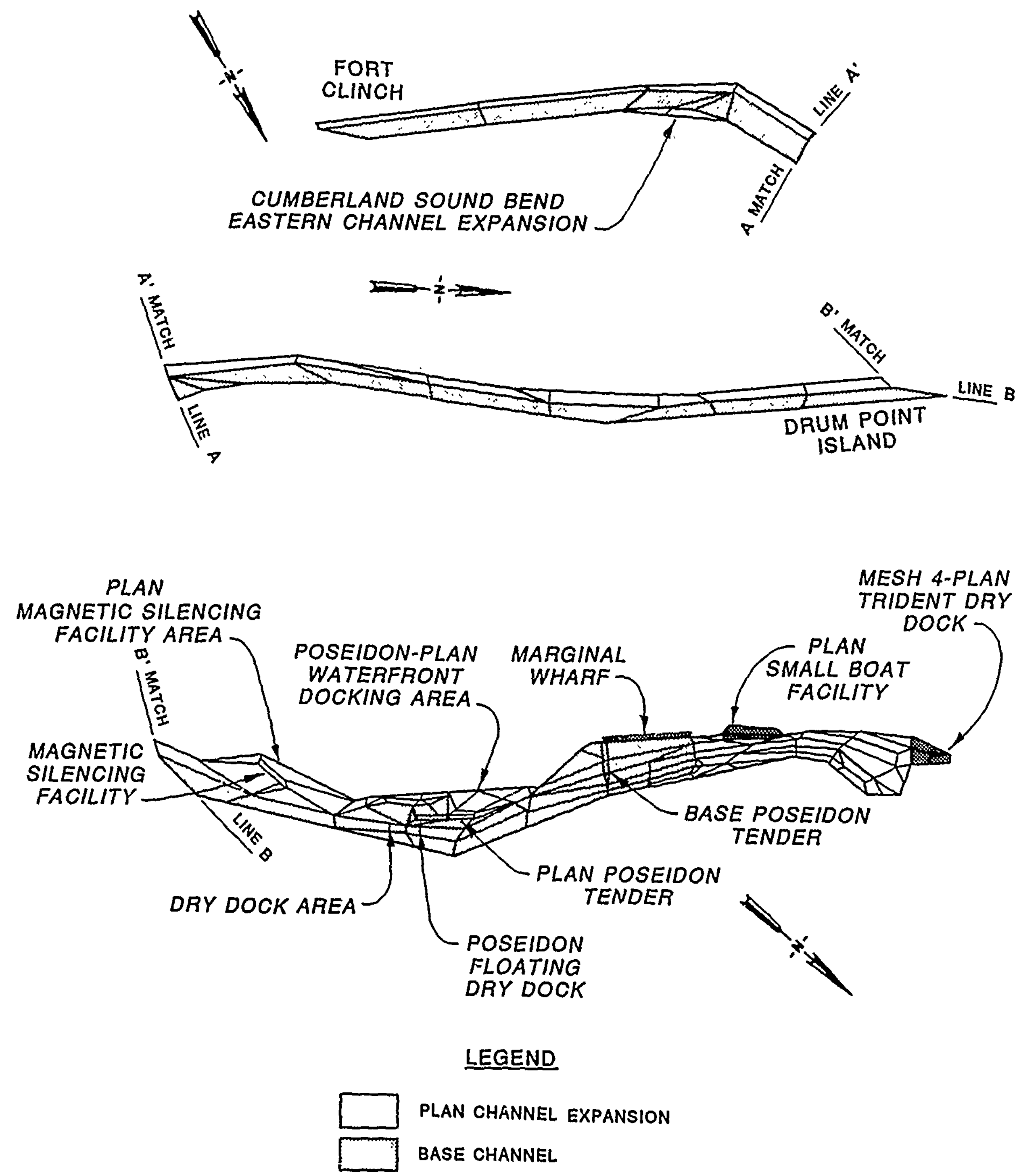


Figure 5. Pre-Trident base and Trident plan channel Mesh 4 detail

model report (Granat and Brogdon, in preparation). Since sedimentation responses are closely related to hydrodynamic variations, a summary of the velocity findings is provided. Basically, small, rather subtle, hydrodynamic differences were identified. The largest base to plan velocity differences occurred in the deepened upper Kings Bay turning basin, where plan condition maximum ebb and flood velocities were reduced by about 1 fps relative to the base condition. Differences at other interior locations were generally less than 0.2 fps. A large recirculation eddy in the northwest corner of the turning basin, downstream of the Trident dry dock, was enhanced during the ebb phase for the plan condition.

43. The deepened and widened Trident plan channel reduced the flow resistance (roughness) and increased flood and ebb flow discharge efficiency of the submarine channel through St. Marys Inlet into Cumberland Sound and Kings Bay. Flood and ebb discharge (flood flow and ebb flow volume transport) as used in the remainder of this report was derived using the continuity check routine in RMA-2V. These values provided a means of comparison in terms of discharge (velocity times depth times width) passing selected cross-sections. They should not be confused with the volume of fresh water within the system. As a result of the increased discharge efficiency of the plan channel along Cumberland Sound, model results demonstrated a slightly reduced flood and ebb discharge at the numerical model tributary boundary locations comparing the plan channel condition to the base channel condition. Approximately 45 percent of the total ocean ebb and flood discharge was associated with the southern tributaries during the base condition; this value was reduced to about 40 percent during the plan condition. This reduction can be attributed to the improved plan channel hydrodynamic discharge efficiency in Cumberland Sound and Kings Bay, i.e., more of the tidal prism flow is transported along Cumberland Sound and through Kings Bay in the plan condition.

44. Figure 6 summarizes the base and plan channel ebb and flood discharge variations for selected areas adjacent to and north of Drum Point Island. The length of each vector on this figure represents the percentage of ocean ebb and flood discharge across each line segment. As previously described, the variations were rather subtle but a consistent trend of increased discharge along Cumberland Sound and through Kings Bay was indicated for the plan channel condition. Although the velocity magnitude through the upper Kings Bay turning basin was reduced for the plan condition, the

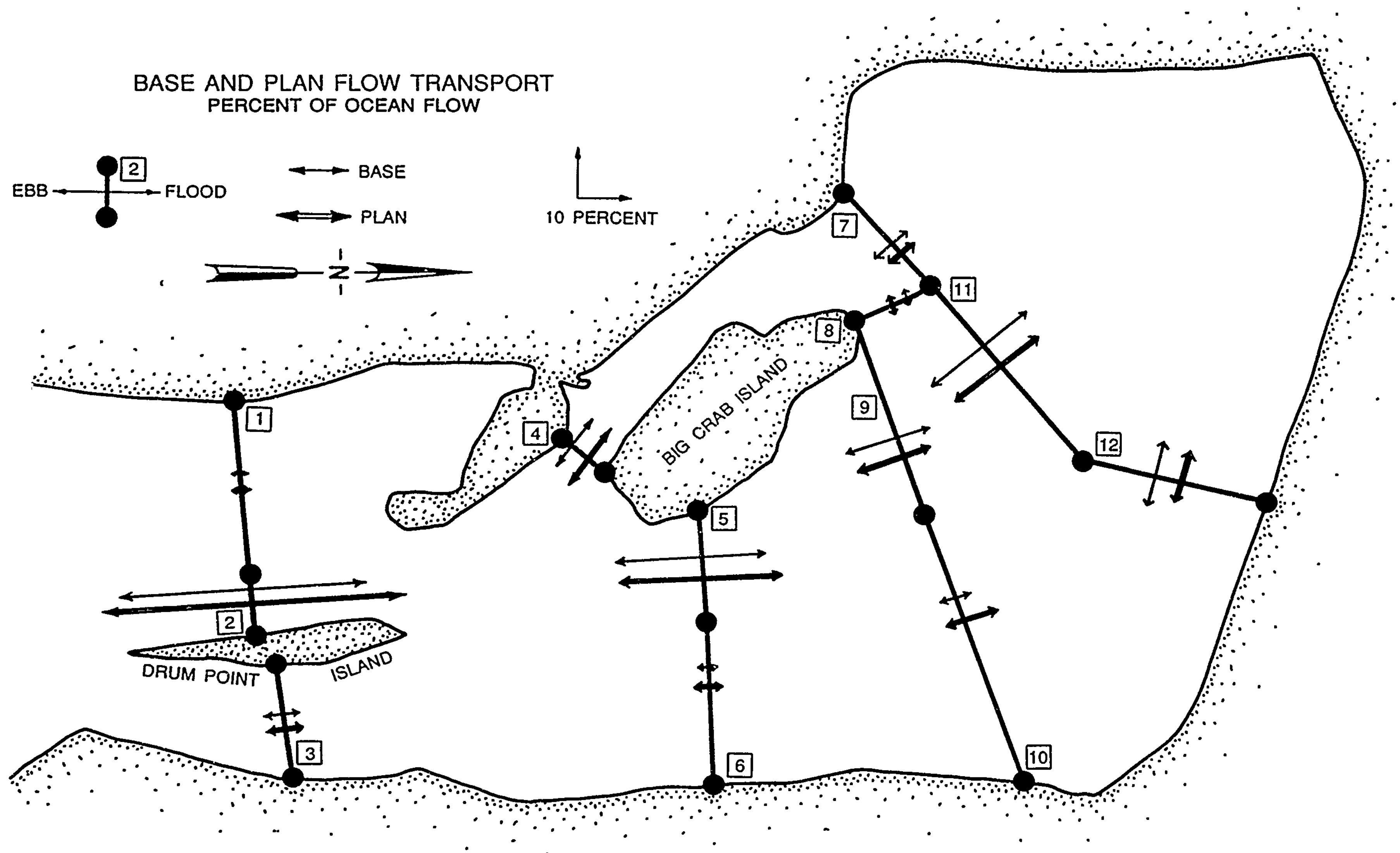


Figure 6. Base and plan discharge comparison

additional cross-sectional area associated with the expanded plan channel resulted in increased discharge through Kings Bay. The circulation through Kings Bay to the marsh areas northwest of Kings Bay and the upper Crooked River was increased for the plan condition relative to the base condition. This circulation changed the phasing relationship between Cumberland Sound and the Crooked River, reducing the travel time, distance, and gradient, resulting in earlier plan condition arrival times (tide and velocity phase). The discharge of ebb and flood flow in the lower south and north forks of the Crooked River was reduced for the plan condition relative to the base condition (more flow was transported through Kings Bay).

45. Figure 7 presents the normalized flow distribution (the percentage of ebb or flood discharge across each line segment divided by the cross-section total ebb or flood discharge) for each of the selected cross-sections. As indicated at the Drum Point Island cross-section (cross-section 1, lines 1, 2, and 3), most of the flow (76-81 percent) was transported across line 2, between the western side of Drum Point Island and the eastern side of Mill Creek Marsh (line 1 is associated with Mill Creek and Mill Creek Marsh). The deepened submarine plan channel increased the relative volume of flow along Cumberland Sound across line 2, while the relative volume along line 3, east of Drum Point Island, was reduced (a 3 to 4 percent reduction).

46. At cross-section 2 (lines 4, 5, and 6), a majority of the base and plan ebb and flood flow (60 to 68 percent) was across line 5, east of Crab Island along northern Cumberland Sound. The total ebb and flood discharge through lower Kings Bay (line 4) was increased during the plan condition; however, the percentage of Trident condition cross-section flood flow through Kings Bay was reduced slightly (from 31 percent to 30 percent) while the ebb flow distribution was increased from 20 percent to 25 percent for the plan condition. Kings Bay did not accommodate all of the increased plan channel lower Cumberland Sound flood discharge (line 2). Plan condition flood discharge at line 5, east of Big Crab Island across northern Cumberland Sound, was also increased relative to the base condition. At cross-section 3 (lines 7 and 8), above upper Kings Bay, a majority of the pre-Trident flow was through Marianna Creek line 7 (68 percent of the flood flow and 80 percent of the ebb flow). For the Trident channel condition, the relative ebb and flood flow distribution through the back channel around upper Crab Island (line 8) was increased by about 5 percent.

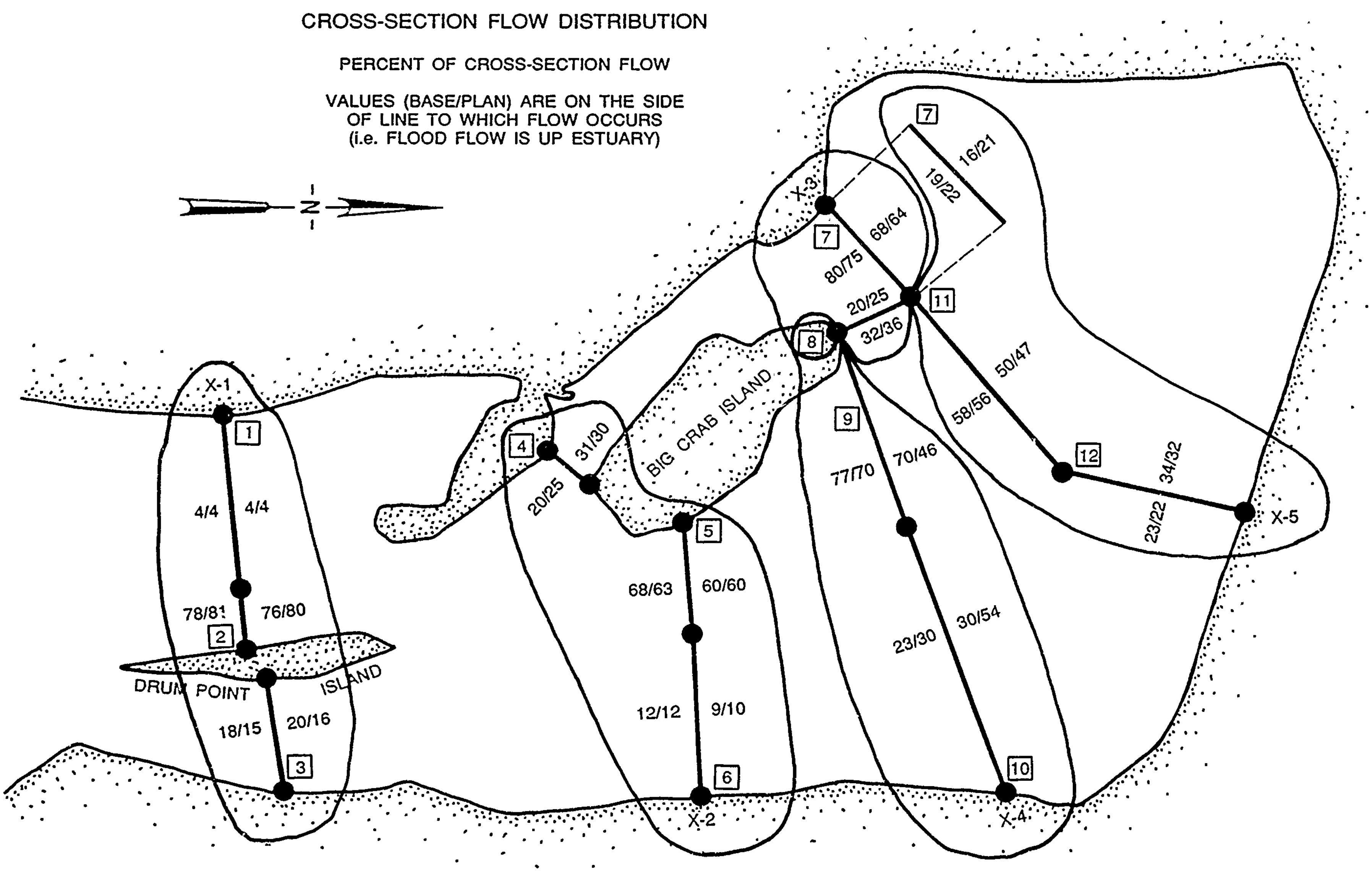


Figure 7. Base and plan normalized flow distribution comparison

47. The largest base to plan flow distribution variations identified were at cross-section 4 (lines 9 and 10). A majority of the pre-Trident flow at this cross-section was along the south fork of the Crooked River (70 percent of the flood flow and 77 percent of the ebb flow). For the Trident channel condition the flood discharge across line 9 (south fork Crooked River) was reduced to 46 percent and the ebb discharge was reduced to 70 percent. The reduced plan flood discharge along the south fork of the Crooked River is attributed to the increased discharge through Kings Bay (lines 4, 7, and 8) resulting in an earlier rise and fall of the water levels to the north of Kings Bay. At cross-section 4, the relative ebb and flood plan discharge across line 10 in Cumberland Sound was increased. The reduced plan condition ebb discharge down the south fork of the Crooked River can likewise be attributed to increased ebb discharge through Kings Bay reducing the water level gradient in the Crooked River.

48. The final cross-section examined (cross-section 5) included Marianna Creek (line 7) and the south and north forks of the Crooked River (lines 11 and 12, respectively). As described in paragraph 44, the distribution of ebb and flood discharge through Marianna Creek was increased for the plan condition relative to the base condition distribution. Plan condition flood and ebb discharge was reduced along both the north and south forks of the lower Crooked River.

49. In summary, the numerical hydrodynamic model predicted subtle but hydrodynamically consistent and rational velocity and circulation differences between the pre-Trident and Trident channel conditions. As expected, the deepened and widened Trident channel was more hydrodynamically efficient than the pre-Trident channel. Although velocity magnitudes were generally reduced in the deepened channel, more flow was discharged through the channel due to increased cross-sectional area and reduced frictional resistance associated with the greater depths.

50. A numerical model sensitivity study was conducted using mixed geometry and boundary forcing conditions (i.e., plan channel geometry with base channel forcing conditions and base channel geometry with plan channel forcing conditions) to investigate potential boundary forcing condition impacts and to provide additional understanding of the complex hydrodynamic characteristics of the Cumberland Sound circulation system. The study findings indicate that velocity impacts were more directly focused along the

main submarine channel and that circulation within Kings Bay was more sensitive to channel geometry differences than to boundary condition differences. These tests confirmed the increased submarine channel flood and ebb discharge associated with the deepened and widened plan channel. Sensitivity study findings are fully described in the base and plan hybrid modeling report (Granat and Brogdon, in preparation).

Channel Sedimentation Differences

51. The predicted submarine channel sedimentation response to the subtle base and plan hydrodynamic variations was dramatic. A complete documentation and discussion of the predicted channel sedimentation differences is provided in Granat and Brogdon (in preparation). In summary, model predictions indicated about a 150 percent increase in required annual plan channel maintenance dredging, from approximately 1.0 million cubic yards per year for the preTrident channel condition to approximately 2.5 million cubic yards per year for the Trident channel condition. Approximately 92 percent (2.3 million cubic yards) of total plan channel shoaling was located within Kings Bay and adjacent facility areas. For the pre-Trident condition approximately 90 percent (0.9 million cubic yards) of the total channel shoaling was associated with the Kings Bay area.

52. Table 4 provides the predicted base and plan channel cohesive, noncohesive, and total (cohesive plus noncohesive) deposition by zone in terms of shoaling volume (cubic yards per year) and shoaling rate (feet per year). Figure 8 provides a schematic of the channel shoaling zone locations and the corresponding submarine channel total shoaling rates. Numeric zones correspond to main channel locations while alphanumeric zones correspond to facility areas adjacent to the main channel. As indicated, high cohesive deposition in the submarine channel is predicted for the zones at and north of the Poseidon docking area (zones 14A through 21). The noncohesive component for these zones is also indicated on Figure 8. No appreciable cohesive deposition is predicted for the channel areas south of zone 14A.

53. Noncohesive deposition in the plan submarine channel was predicted to increase by about 100 percent, from about 0.2 million cubic yards per year for the base channel condition to about 0.4 million cubic yards per year for the plan channel condition. Reduced plan channel noncohesive shoaling volume

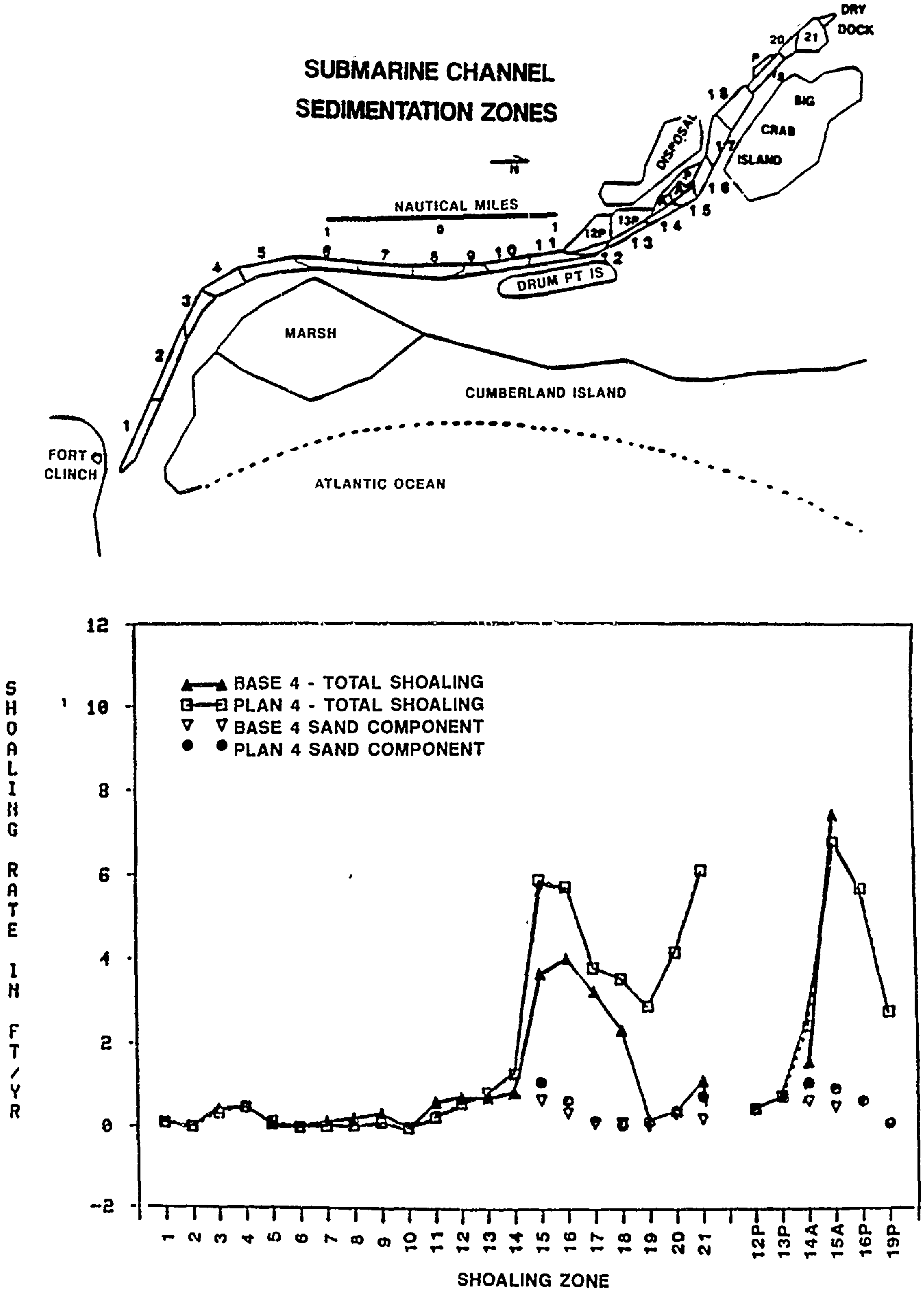


Figure 8. Base and plan channel total sedimentation (cohesive plus noncohesive)

and rate was predicted between zones 7 and 12. With the exception of lower Kings Bay (zone 18), increased plan channel noncohesive deposition (volume and rate) was predicted for the channel areas above zone 12. Noncohesive deposition comprised about 22 percent of the total predicted pre-Trident channel yearly maintenance dredging requirement and about 18 percent of the predicted Trident channel maintenance requirement.

54. High cohesive deposition rates within Kings Bay accounted for most of the base and plan channel predicted annual maintenance material. Cohesive deposition within the plan channel was predicted to increase by about 150 percent, from about 0.8 million cubic yards per year for the pre-Trident channel to about 2.0 million cubic yards per year for the Trident channel. Plan channel cohesive deposition above zone 14 was predicted to increase everywhere except at zone 15A. The reduced cohesive deposition at zone 15A was associated with the development of the adjacent Poseidon waterfront docking area (zone 16P) which was also predicted to be a high shoaling area (i.e., available shoaling material was distributed across a much larger area).

55. In summary, the pre-Trident Kings Bay area was an efficient sediment trap for cohesive suspended sediments. The additional channel widening, deepening, and extension within this high deposition region was predicted to dramatically increase the Trident channel yearly average maintenance dredging requirement. In addition to the increased channel area, the increased plan channel shoaling volumes and rates in Kings Bay were the result of the increased flood and ebb discharge through Kings Bay and the reduced current velocities associated with increased plan channel cross-sectional area. As discussed in paragraph 40, however, the as-built Trident channel condition differed somewhat from the modeled conditions so model sedimentation predictions may also differ somewhat from actual field conditions.

Sensitivity Studies

56. Numerical sediment model sensitivity studies were conducted using the hydrodynamic output data from the RMA-2V sensitivity study (see paragraph 50) conducted with the mixed geometry and boundary forcing conditions (i.e., base geometry with plan channel boundary forcing conditions and plan geometry with base channel forcing conditions) to investigate model sedimentation sensitivity to hydrodynamic boundary forcing conditions. Although the

resulting shoaling distributions (location, type, and amount) varied somewhat between the actual base or plan condition and the corresponding geometry sensitivity test (the mixed geometry and boundary condition), the total submarine channel shoaling volume for each geometry condition (base or plan channel geometry) agreed within 4 percent. These findings indicate that the predicted channel shoaling rates were sensitive to the channel geometry condition and the resulting interior hydrodynamic variations and were fairly insensitive to base and plan channel hydrodynamic boundary forcing condition differences. See Granat and Brogdon (in preparation) for a detailed description of the sensitivity results.

57. Boundary condition cohesive suspended sediment concentration was another type of sensitivity analysis performed. The base channel RMA-2V hydrodynamic results were used to examine submarine channel sedimentation sensitivity to mesh initial and boundary suspended sediment concentrations of 100, 70, 50, and 25 mg/ℓ. The findings indicated a nonlinear response trend between submarine channel shoaling rate and the specified cohesive suspended sediment concentration. A 30 percent reduction in specified suspended sediment concentration, from 100 mg/ℓ to 70 mg/ℓ, resulted in a corresponding 6 percent reduction in total submarine channel cohesive deposition. A 50 percent reduction in specified concentration, to 50 mg/ℓ, resulted in about a 20 percent reduction in total submarine channel cohesive deposition. Little shoaling rate variation (a 3 percent reduction) resulted when the specified concentration was further reduced from 50 to 25 mg/ℓ. These findings indicated that in the modeling procedure developed for the Kings Bay study, the submarine channel shoaling rate was somewhat sensitive to specified suspended sediment concentration conditions between 50 and 70 mg/ℓ, but was relatively insensitive to concentration variations between 70 and 100 mg/ℓ or between 25 and 50 mg/ℓ. The findings suggest that the predicted submarine channel cohesive sedimentation was associated with sediment redistribution from within the interior portions of the modeled area.

58. The complete STUDH modeling procedure for these sensitivity tests included the initial nonerodible bed coldstart and the bed structure hotstart tidal cycles (see Granat et al. 1989 for a complete description). Each of these tidal cycles began with the specified uniform initial sediment concentration throughout the mesh. This procedure was conducted for each sediment concentration (mesh initial and boundary conditions). The result was a

hydrodynamically developed bed structure and concentration field using the prescribed conditions for initializing the final model sensitivity tidal cycle (a hotstart bed structure and concentration field condition). The 25 mg/ℓ concentration was unrealistically low for the Cumberland Sound system with respect to the bed structure development and was below the threshold limits of the model, but was included for completeness. The modeling approach included the interaction of the bed conditions and the hydrodynamics (shear stress, and advective and diffusive transport) and the interrelationships between these conditions and the initial, boundary, and developed bed conditions, all of which contribute to the nonlinear nature of the model response. It is emphasized that the sensitivity findings are associated with the modeling approach (including the long-term extrapolation) and may not be directly applicable to actual field conditions and/or responses; field conditions may be more responsive to short-term boundary concentration conditions than suggested by the model sensitivity findings.

Potential Sediment Sources and Redistribution

59. The model-predicted sedimentation characteristics (deposition and erosion) across the entire computational mesh were examined to help identify potential source areas and potential areas of impact. Before this information is presented, the qualifications and the additional caution stressed in paragraphs 18, 19, 37, and 38 is reiterated: the developed modeling procedure has been verified only for the pre-Trident submarine channel sedimentation history. Quantitative assessment of sedimentation responses outside of this area, especially in those areas directly affected by the wetting and drying algorithm (i.e., the marsh and sand flat areas), is not recommended. Only general qualitative trend-type comparisons and assessments should be made for these unverified areas.

60. For this additional trend analysis, the base and plan cohesive and noncohesive STUDH sedimentation predictions were linearly interpolated into a rectangular 400 by 400 array. The results are presented in consistent arbitrary linear sedimentation units (CALSU). Figure 9 illustrates the model predicted base condition cohesive sedimentation (erosion and deposition) pattern and Figure 10 illustrates the model-predicted plan condition cohesive sedimentation pattern. The St. Marys Inlet area to the northeast of Fort

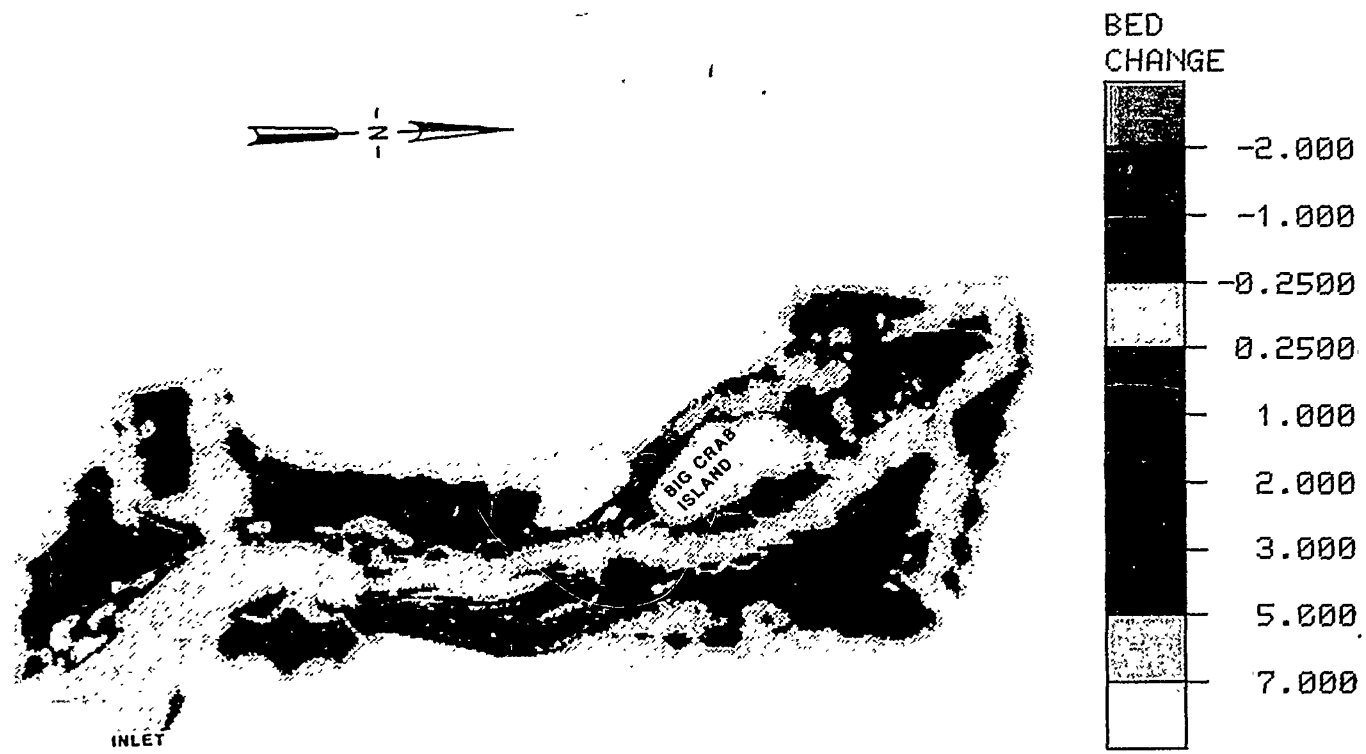


Figure 9. Pre-Trident base channel cohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units

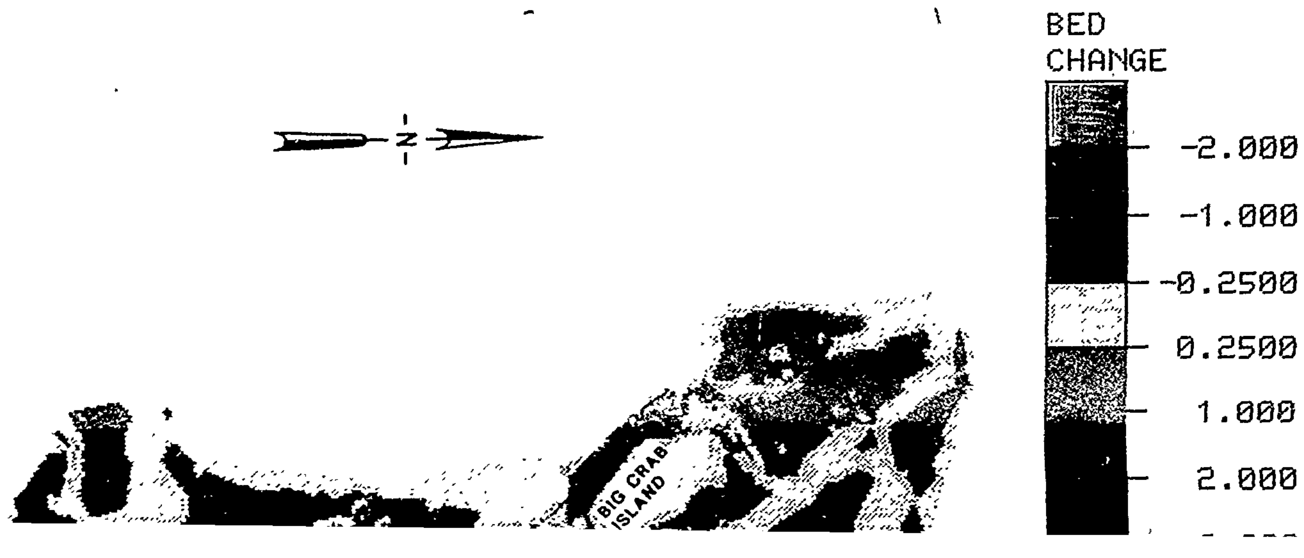


Figure 9. Pre-Trident base channel cohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units

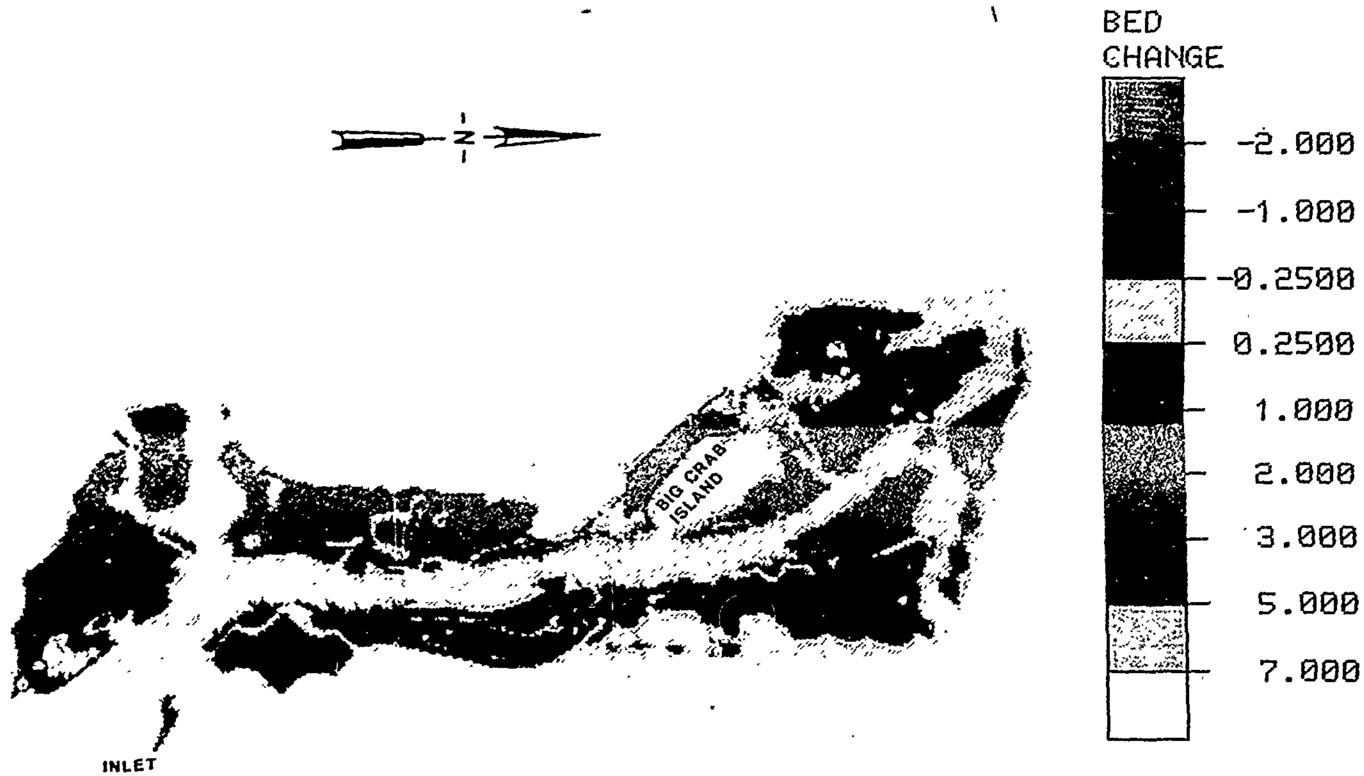
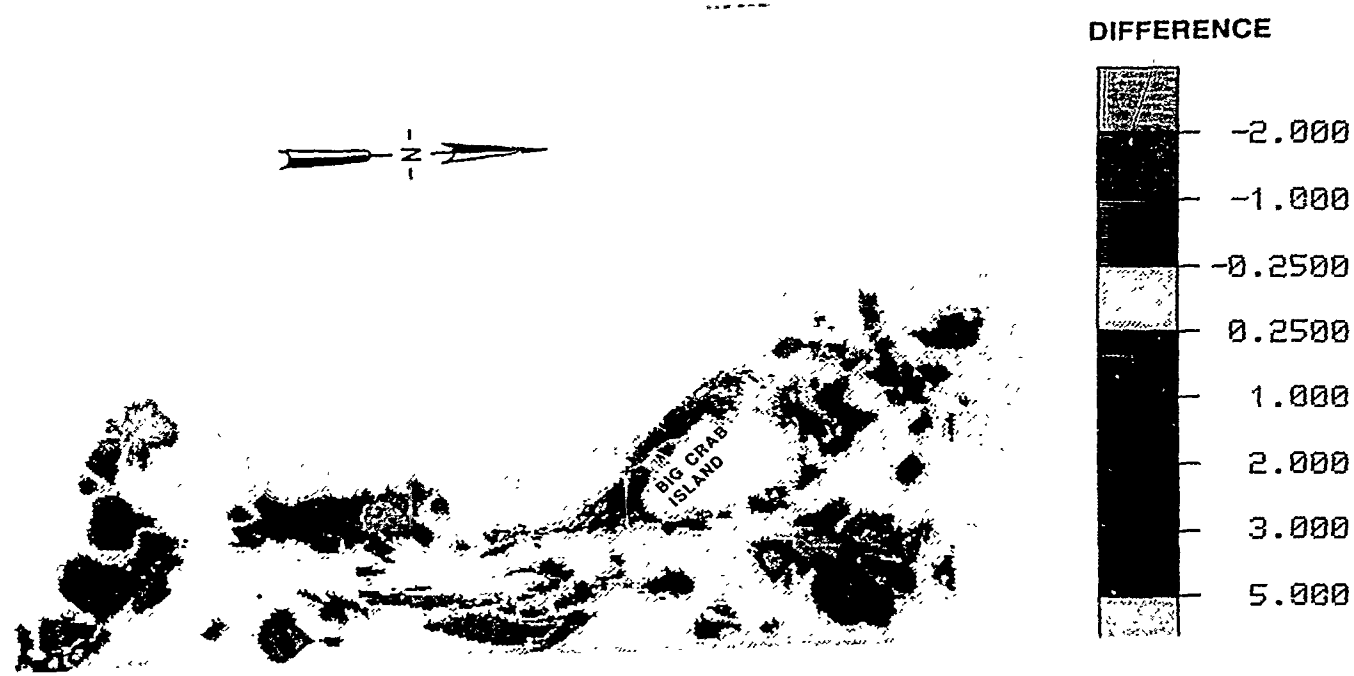


Figure 10. Trident plan channel cohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units



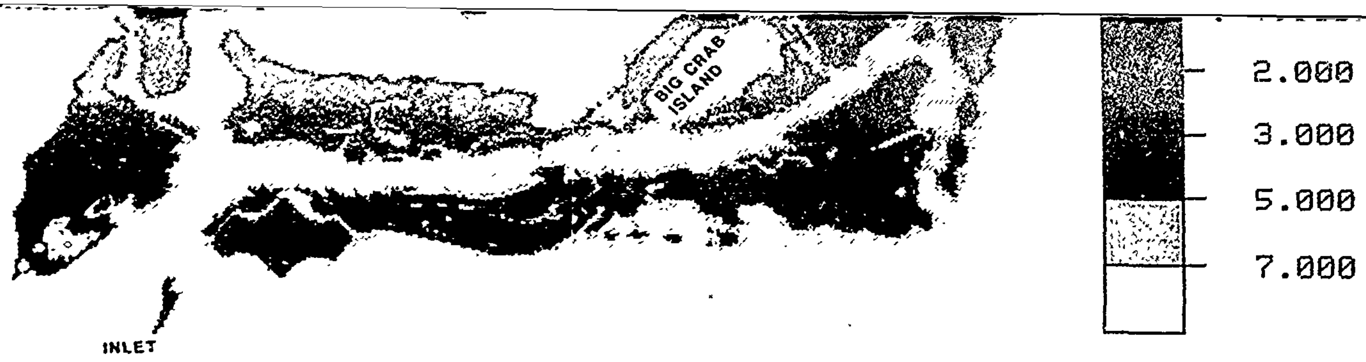


Figure 10. Trident plan channel cohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units

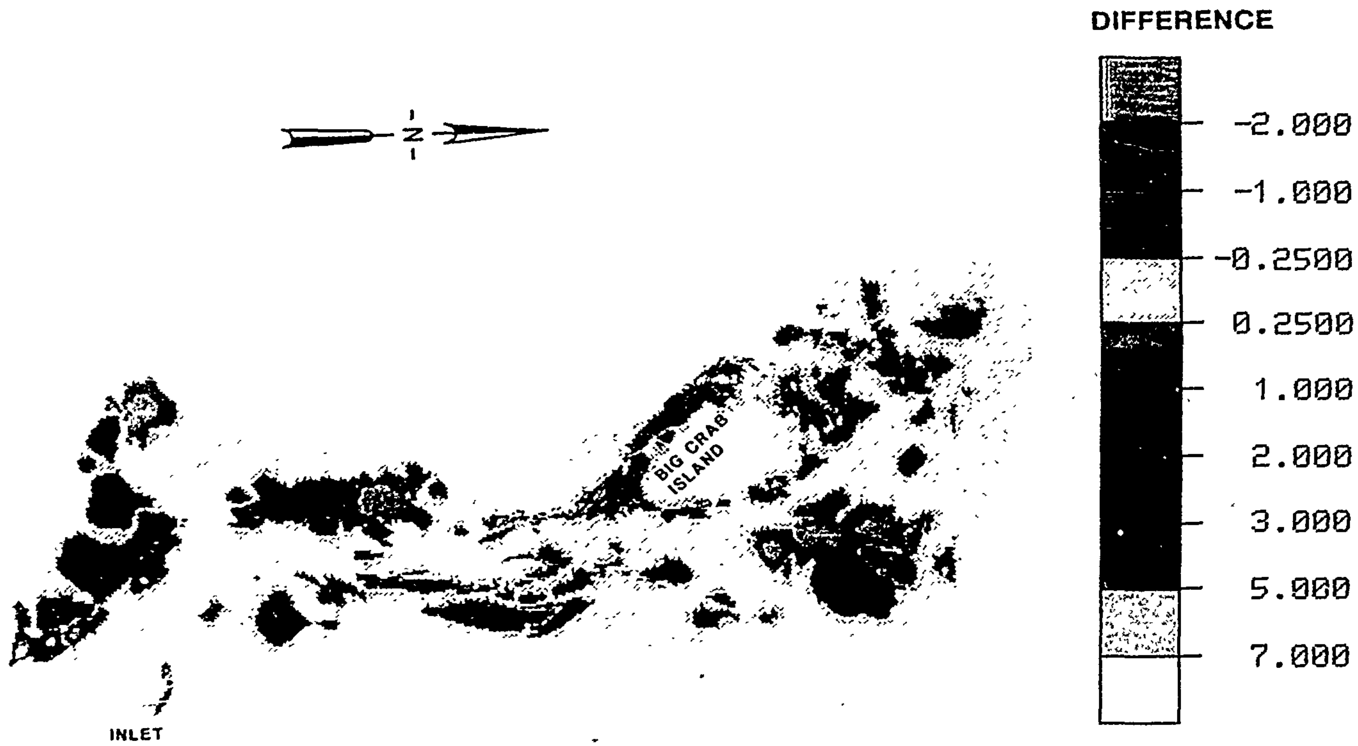


Figure 11. Trident plan channel minus pre-Trident base channel cohesive sedimentation. Note: Difference is given in consistent arbitrary linear sedimentation units

Clinch was part of a separate Kings Bay coastal processes numerical modeling effort (Vemulakonda et al. 1988) and was excluded from these and following figures. As presented, generally subtle sedimentation differences between the base and plan channel conditions existed. Basically, depositional and erosional trends were quite similar, however, small variations in sedimentation magnitude and extent were indicated. The largest and most noticeable variations were within Kings Bay and at isolated areas close to the numerical model boundary locations. Variations at these locations are not surprising; model predictions near boundaries are generally unreliable and the shoaling differences within Kings Bay have previously been described. Most of the cohesive sedimentation activity was in shallow water and marsh areas. With the exception of the Kings Bay area, little to no cohesive sedimentation (less than 0.25 CALSU per year) was predicted in the primary channel areas.

61. The region to the east, northeast, and southeast of Drum Point Island demonstrated the most extensive areas of predicted cohesive erosional characteristics for both the base and plan conditions. Water depths to the east (between Drum Point Island and Cumberland Island) and northeast (between Drum Point Island and Stafford Island) were generally less than 10 ft deep, while depths to the southeast, along the naturally deep channel west of Cumberland Island adjacent to Beach Creek Marsh (Figure 1), were between 20 and 30 ft deep. Other predicted erosional areas included the shallow-water regions adjacent to marsh areas to the west of the submarine channel in Cumberland Sound and to the east and northeast of Big Crab Island. The extensive marsh areas themselves were generally predicted to be sites of cohesive sediment deposition for both the base and plan conditions.

62. Figure 11 presents a summary of plan minus base cohesive sediment model prediction differences. Areas with negative difference values do not necessarily represent erosional areas. In general, these areas were associated with marsh and shallow water areas that were sites of predicted sediment accumulation for both base and plan channel conditions (see Figures 9 and 10 and paragraph 61). The Trident plan channel condition was predicted to have lower rates of sediment accumulation in these marsh areas relative to the base channel condition.

63. The three largest regions of negative cohesive sedimentation difference (actually reduced plan condition deposition relative to the base condition), in decreasing geographic extent, were the shallow-water area in

Cumberland Sound between the south and north forks of the Crooked River, the Mill Creek marsh area to the west of the submarine channel between Kings Bay and the St. Marys River, and the marsh area between Amelia and Jolly Rivers. Other regions of predicted plan condition cohesive sedimentation reduction included the area between Drum Point Island and Cumberland Island, the marsh region between Jolly and St. Marys Rivers, and the marsh region above upper Kings Bay between Marianna Creek and the back channel around Crab Island. These regions were also predicted cohesive depositional areas for both the base and plan channel conditions. Relative to the base condition, the interior Kings Bay area demonstrated the greatest (geographic extent and magnitude) plan condition cohesive depositional increases.

64. The presented results can be interpreted to indicate that the increased plan channel size and associated increased transport (flood and ebb discharge) and reduced velocities through Kings Bay (circulation and hydrodynamic changes) enhanced the trapping efficiency of Kings Bay, resulting in the dramatic increases in predicted plan channel maintenance dredging requirement. The increased channel deposition was balanced by a reduced deposition at the indicated marsh areas. The additional volume of cohesive sediments predicted to accumulate in the Trident plan channel was material that the model predicted would have deposited on and adjacent to the marsh areas under pre-Trident channel conditions. The model predicted that based on associated changes in the hydrodynamic and sedimentation processes more of the available cohesive sediments would preferentially deposit in the plan Kings Bay channel instead of in the marsh and shallow water areas as indicated in the pre-Trident condition.

65. The following analogy is provided in an attempt to relate and qualify indicated model trends with generalized prototype (field) characteristics and processes. In the prototype, productive marsh areas can be considered to be sites of sediment accumulation (i.e., they keep up with sea-level rise) and they can be sources of episodic sediment supply (i.e., they can act as temporary storage or trap areas for sediments during certain tidal or environmental conditions and as sources of sediments during other conditions). Long-term tidal conditions (i.e., fortnightly neap to spring tidal elevation and range variations) and wave-induced transport processes in the prototype can greatly modify short-term sedimentation responses and limit deposition, especially in shallow water regions. The lack of this episodic

cycling in the developed modeling procedure (i.e., average tide condition) and the use of a long-term extrapolation can explain anomalously high shoaling volumes predicted in marsh areas in the present modeling application.

66. As discussed in the introduction, the hybrid modeling system was developed to predict average maintenance dredging requirements for the enlarged submarine channel and port facilities. The modeling procedure, based on a long-term extrapolation from an average short-term condition, was found to provide an excellent verification to available submarine channel shoaling history for the pre-Trident condition. In shallow-water regions, however, the long-term extrapolation does not provide the model with the capability to limit deposition as would be the case in the prototype. Periods of increased tidal and wave energy that can reduce the amounts of long-term deposition in the prototype shallows are not modeled. A greater consequence of the long-term extrapolation is the lack of a direct feed-back between the sediment model (bed-change) and the hydrodynamic model (velocity or shear stress), i.e., as deposition continues and the bed approaches the water surface elevation, deposition will be limited by the associated increased shear stress and the reduced volume of water (source material).

67. For the above reasons, and as stressed throughout this report, quantitative assessments of model predictions outside the verified channel areas should not be performed. As stated in the introduction, model results for these areas should be used only to predict general trends and identify potential impact areas for consideration in modifying or intensifying the field monitoring and evaluation program. The excellent model verification to the pre-Trident channel sedimentation history and the findings of all the sensitivity studies provide additional support in utilizing the model predictions for this purpose. Also, the indicated general cohesive sedimentation trends and the sediment redistribution between the base and plan conditions are in concert with the base and plan hydrodynamic trends previously described.

68. Figure 12 illustrates the model predicted base condition noncohesive sedimentation pattern and Figure 13 illustrates the model predicted plan condition noncohesive sedimentation pattern. As with the cohesive sediments, subtle sedimentation pattern variations were illustrated. Base and plan condition noncohesive depositional and erosional trends were generally similar with only small differences in sedimentation magnitude and extent

indicated. Areas of predicted active noncohesive sedimentation (erosion or deposition values greater than 0.25 CALSU per year) were smaller than areas of predicted active cohesive sedimentation. The extent (geographic area) of erosional areas was almost equal to the extent of depositional areas for noncohesive sediments while depositional areas were much more numerous than erosional areas for cohesive sediments. Most of the noncohesive sedimentation activity was predicted along the primary channel areas associated with the lower Cumberland Sound tributaries (St. Marys, Jolly, and Amelia Rivers) to the St. Marys Inlet area, and the north and south forks of the Crooked River. In general, little to no noncohesive sedimentation (less than 0.25 CALSU per year) was predicted in the marsh areas; the western portion of Beach Creek Marsh was a notable exception illustrating some noncohesive erosion. The model, based on average tidal currents without additional wave-induced energy, predicted a reduced rate of noncohesive erosion across Beach Creek for the plan condition relative to the base condition.

69. The large rates of noncohesive sedimentation adjacent to the tributary boundaries may be associated with initial model responses and adjustments to the boundary conditions. As stated in paragraph 60, model predictions near boundaries are generally unreliable. Areas of high noncohesive deposition immediately adjacent to areas of high erosion can indicate model instabilities due to misassigned sediment grain size specification (a large disequilibrium between sediment grain size and transport potential). A review of the noncohesive sediment grain size distribution (Figure 4) and the sedimentation results presented in Figures 12 and 13 suggests the possibility that a coarser grain size could have been used at the St. Marys and Cumberland River boundaries (coarser than 0.35 mm) and along portions of the north fork of the Crooked River (coarser than 0.125 mm). No sedimentation history was available for these areas and the available limited field sediment samples could not be used to resolve this uncertainty.

70. The high noncohesive erosion rates indicated in the north and south forks of the Crooked River for the base condition were generally reduced for the plan condition. Noncohesive erosional rates for the plan condition in Cumberland Sound east of Big Crab Island were generally increased relative to the base condition. These results are in concert with the hydrodynamic findings of reduced plan condition discharge in the lower north and south forks of the Crooked River and the increased plan condition discharge east of

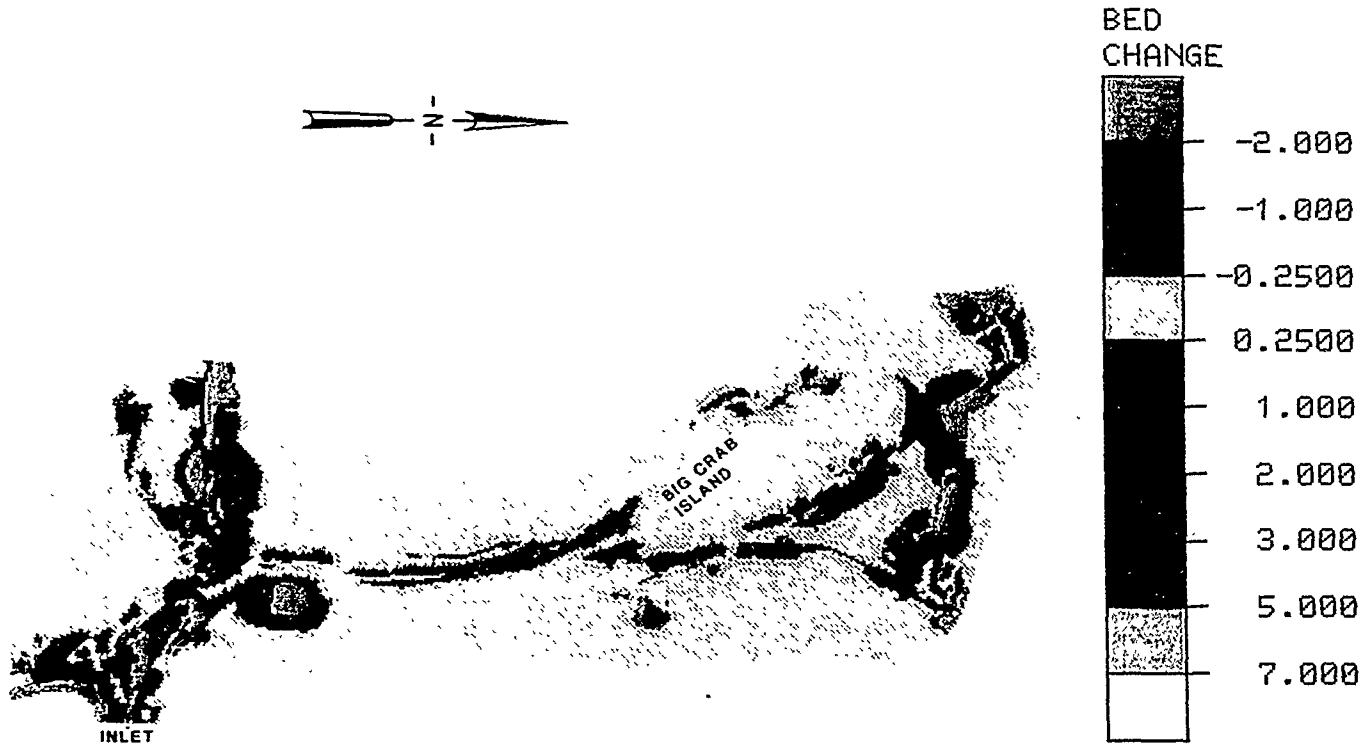
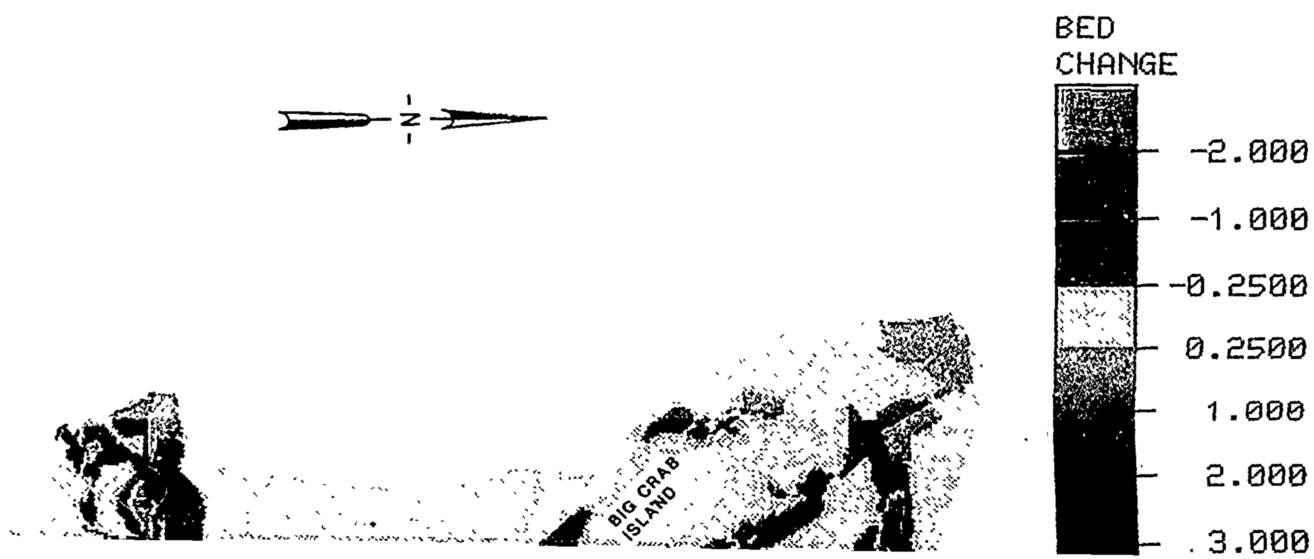


Figure 12. Pre-Trident base channel noncohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units



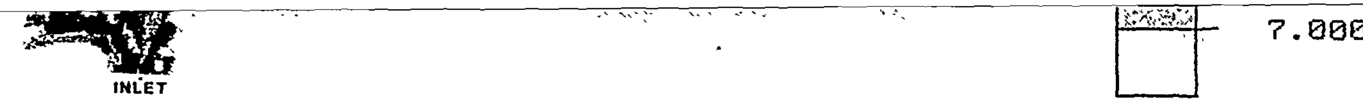


Figure 12. Pre-Trident base channel noncohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units

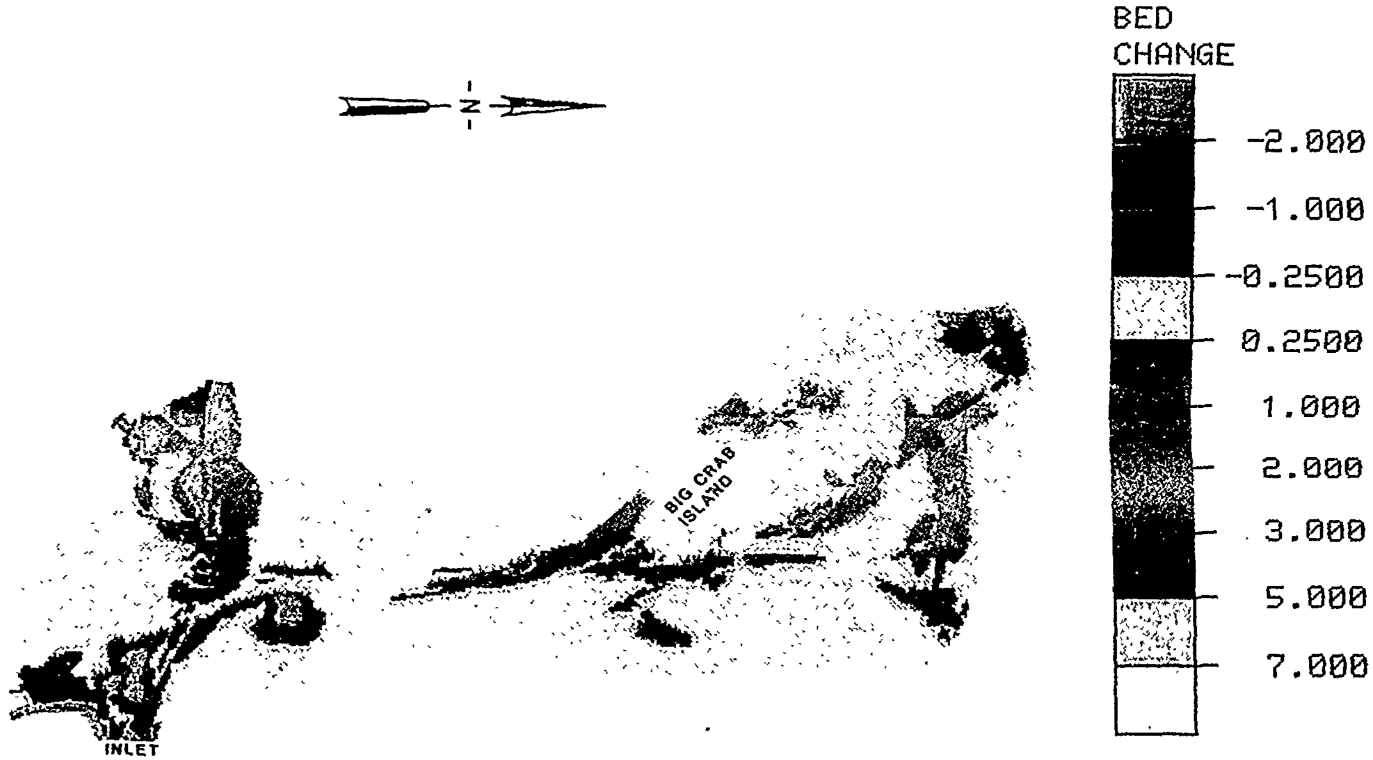
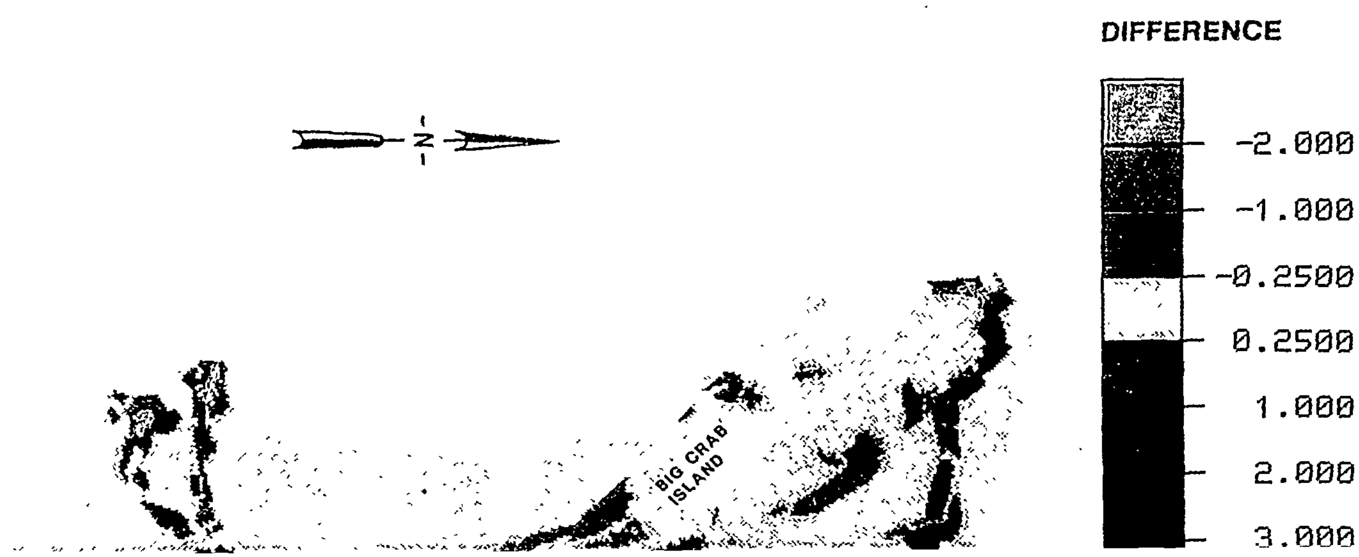


Figure 13. Trident plan channel noncohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units



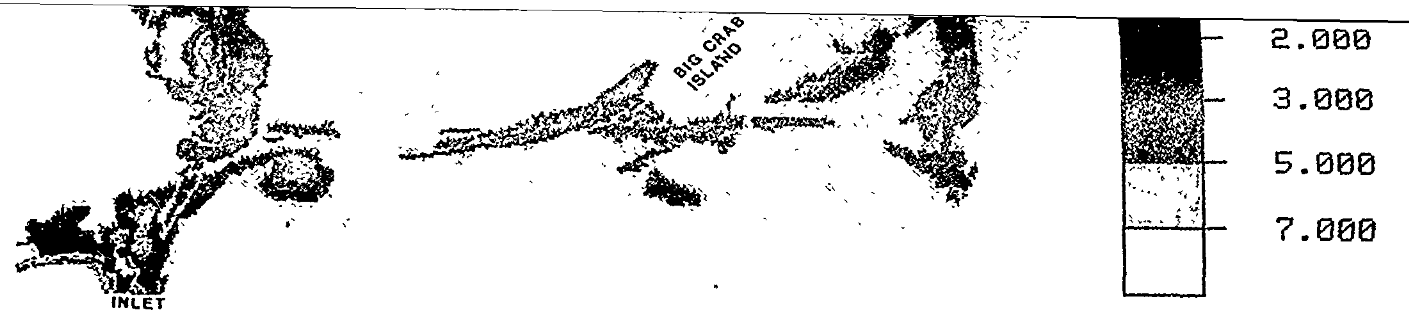


Figure 13. Trident plan channel noncohesive sedimentation. Note: Bed change is given in consistent arbitrary linear sedimentation units

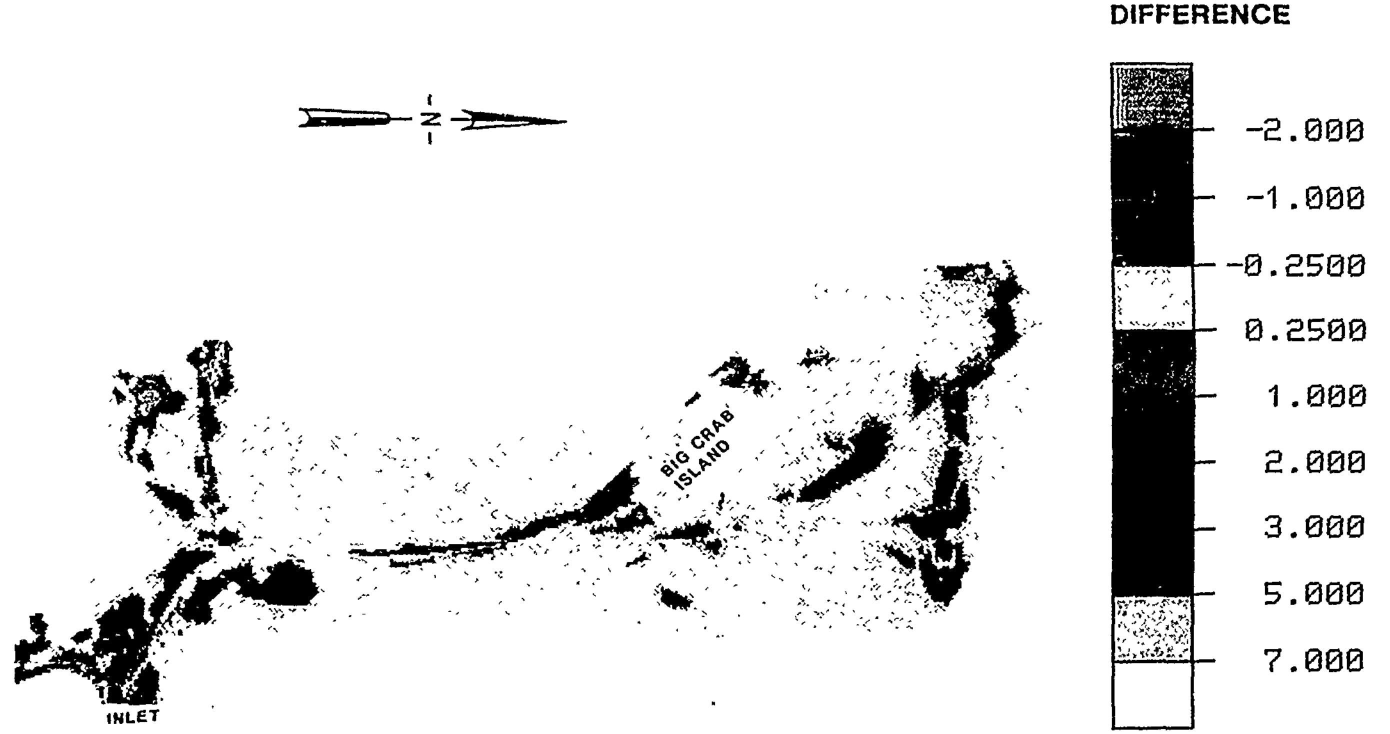


Figure 14. Trident plan channel minus pre-Trident base channel noncohesive sedimentation. Note: Difference is given in consistent arbitrary linear sedimentation units

Big Crab Island (see Granat and Brogdon (in preparation) for more detailed hydrodynamic information). In each of the above cases, discharge is directly related to velocity magnitude and erosion potential since depth did not change between the base and plan tests at these locations.

71. As presented in Table 4 and Figures 12 and 13, noncohesive deposition in upper Kings Bay (zones 20 and 21) was increased for the plan condition relative to the base condition. Little noncohesive sedimentation occurred between zones 17 and 19 in either the base or plan submarine channel. Noncohesive deposition in Cumberland Sound between the entrance to Kings Bay and the area northwest of Drum Point Island generally increased for the plan condition relative to the base condition. The geographic extent of the Cumberland Sound erosional area to the west of the submarine channel south and west of Drum Point Island was somewhat reduced between the base condition and the plan condition.

72. Figure 14 presents the plan minus base noncohesive sedimentation differences. As in Figure 11, this illustration should be carefully interpreted; areas of negative or positive values do not necessarily mean erosional or depositional areas, respectively. For example, as described in paragraph 68, the positive values along the western portion of Beach Creek Marsh are associated with reduced noncohesive erosion rates for the plan condition relative to the base condition. Similarly, the positive values illustrated in the south fork of the Crooked are associated with reduced plan condition erosion relative to the base condition. Noncohesive erosion in Cumberland Sound to the east of Big Crab Island was increased during the plan condition relative to the base condition. Velocities, transport potential, and transport capacity in this area were increased for the plan condition relative to the base condition. In summary, the indicated general cohesive and noncohesive sedimentation trends and redistribution are in concert with the previously described base and plan hydrodynamic findings.

PART IV: CONCLUSIONS

73. The modeling procedure developed to predict average currents and long-term average maintenance dredging requirements for the Kings Bay submarine channel was used to identify potential sediment sources and sediment redistribution associated with the Trident channel expansion. Excellent numerical model to field submarine channel sedimentation verification has previously been demonstrated for the pre-Trident condition. Model predictions indicated about a 150 percent increase in required annual plan channel maintenance dredging, from approximately 1.0 million cubic yards per year for the pre-Trident channel condition to approximately 2.5 million cubic yards per year for the Trident channel condition. Numerical model sensitivity studies indicate that the predicted shoaling rates were sensitive to the channel geometry condition and the resulting interior hydrodynamic circulation variations and were fairly insensitive to base and plan channel hydrodynamic boundary forcing condition differences.

74. Cohesive and noncohesive sedimentation patterns across the computational mesh are illustrated for the pre-Trident base and Trident plan channel conditions. Quantitative assessment of the indicated sedimentation responses outside of the verified channel areas is not recommended. Only general qualitative trend-type comparisons and assessments should be made for these unverified areas. With the exception of Kings Bay and areas close to the numerical model boundaries, generally, subtle sedimentation differences in geographic extent and/or magnitude were identified. The indicated patterns and the differences between the base and plan conditions were in agreement with the identified subtle base and plan hydrodynamic differences.

75. Active cohesive sedimentation (erosion or deposition rates greater than 0.25 CALSU per year) was predicted over a much larger geographic extent than noncohesive sedimentation activity. Active cohesive deposition occurred in the marshes and shallow water areas and in Kings Bay during both the base and plan conditions. With the exception of the Kings Bay area, little to no cohesive erosion or deposition occurred in the primary channel areas. The pre-Trident Kings Bay area was an efficient sediment trap for cohesive sediments. The additional Trident channel widening, deepening, and extension within this high deposition region was predicted to increase trapping efficiency. The increased plan channel area and associated increased flood and

ebb discharge (transport) and reduced current velocities within Kings Bay increased the predicted cohesive shoaling volumes and rates. The model predicted that Kings Bay would become a preferred site for cohesive deposition. The increased cohesive deposition predicted for the Trident Kings Bay was associated with material the model predicted would have deposited on and adjacent to the marsh areas under pre-Trident channel conditions, i.e., relative to the base condition some of the marsh areas were predicted to be potential sites of reduced cohesive deposition during the plan condition.

76. Most of the noncohesive sedimentation activity was predicted along the channel areas associated with the lower Cumberland Sound tributaries and the north and south forks of the Crooked River. Minor plan channel noncohesive sedimentation impacts were identified compared to the predicted potential cohesive sedimentation impacts. With the exception of the Beach Creek Marsh area, little to no noncohesive sedimentation (erosion or deposition) was predicted in the marsh areas during either the base or plan condition. A reduced rate of noncohesive erosion was predicted by the model for the Beach Creek Marsh area during the plan condition relative to the base condition.

77. The objective of this task to identify potential sediment sources and sediment redistribution associated with the Trident channel expansion has been accomplished. Predicted areas of potential sedimentation impact or change have been identified and are illustrated.

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Table 1

RMA2-V Hydrodynamic Coefficients

Type	Description	Turbulent Exchange Coefficient lb-sec/sq ft	Manning's n
1	Small channel	100	0.025
2	Normal channel	100	0.020
3	Smooth channel	100	0.015
4	Main marsh	200	0.050
5	Secondary marsh	170	0.040
6	Marsh/channel transition	150	0.030
7	Ocean	500	0.020
8	Dock facility	300	0.030
9	Dry dock/tender	70	0.030

Table 2

Cohesive Sedimentation Coefficients

Coefficient	Cycle 1	Cycle 2	Cycle 3
Crank-Nicholson THETA	0.66	0.66	0.66
Critical shear stress deposition, N/sq m	0.05	0.05	0.05
Dry weight density of freshly deposited layer, kg/cu m	300	300	300
Particle specific gravity	2.65	2.65	2.65
Erosion rate constant, kg/sq m/sec	0.002	0.002	0.002
Effective diffusion, sq m/sec	50	50	50
Boundary inflow sediment concentration, kg/cu m	0.10	0.10	0.10
Exterior boundary particle settling velocity, m/sec	0.0	0.0	0.0
Interior boundary particle settling velocity, m/sec	0.0006	0.0003	0.0003
Critical shear stress particle erosion, N/sq m	0.15	0.12	0.12
Sediment bed initialization	Non-eroding	hot start cycle 1	hot start cycle 2
Initialization of suspended sediment concentration	0.10	0.10	hot start cycle 2

Table 3

Noncohesive Sediment Coefficients

Crank-Nicholson THETA	0.66
Particle specific gravity	2.65
Particle shape factor	0.70
Length factor for deposition (times depth)	0.50
Length factor for erosion (times depth)	10.0
Effective diffusion, sq m/sec	250
Boundary inflow sediment concentration, kg/cu m	0.01
Median sediment grain size D_{50}, mm	
Coarse sand	0.70
Medium sand	0.35
Fine sand	0.125
Particle settling velocity, m/sec	
Coarse sand	0.090
Medium sand	0.045
Fine sand	0.0105
Manning's n value	
Ocean	0.025
Channel bend at lower Cumberland Sound	0.015
Channel bend at Kings Bay entrance	0.010
All other areas	0.020

Table 4

Numerical Model Shoaling Predictions

Zone	Area 1,000 sq ft Base	Area 1,000 sq ft Plan	Cohesive Shoaling 1,000 cu yds/yr Base	Cohesive Shoaling 1,000 cu yds/yr Plan	Cohesive Shoaling ft/yr Base	Cohesive Shoaling ft/yr Plan	Noncohesive Shoaling 1,000 cu yds/yr Base	Noncohesive Shoaling 1,000 cu yds/yr Plan	Noncohesive Shoaling ft/yr Base	Noncohesive Shoaling ft/yr Plan
1	1338	1688	NA	NA	NA	NA	5	6	0.1	0.1
2	1485	1839	NA	NA	NA	NA	NA	NA	NA	NA
3	1077	1641	NA	NA	NA	NA	18	21	0.4	0.3
4	1304	1722	NA	NA	NA	NA	24	31	0.5	0.5
5	1511	1997	NA	NA	NA	NA	5	11	0.1	0.1
6	965	2264	NA	NA	NA	NA	NA	NA	NA	NA
7	892	1489	NA	NA	NA	NA	5	2	0.2	NA
8	796	1580	NA	NA	NA	NA	7	3	0.2	0.1
9	594	848	NA	NA	NA	NA	8	4	0.4	0.1
10	661	1147	NA	NA	NA	NA	NA	NA	NA	NA
11	834	1221	NA	NA	NA	NA	19	12	0.6	0.3
12	710	710	NA	NA	NA	NA	20	16	0.7	0.6
13	718	718	NA	NA	NA	NA	19	22	0.7	0.8
14	666	666	NA	NA	NA	NA	21	32	0.9	1.3
15	661	661	73	117	3.0	4.8	16	27	0.7	1.1
16	1109	1109	151	207	3.7	5.1	15	27	0.4	0.7
17	1966	1966	229	264	3.1	3.6	9	14	0.1	0.2
18	2305	2305	177	297	2.2	3.5	11	7	0.1	0.1
19	NI	1646	(9)	167	(0.2)	2.8	(NA)	10	(0.1)	0.2
20	NI	709	(2)	99	(0.1)	3.8	(9)	11	(0.4)	0.4
21	NI	2137	(73)	423	(0.9)	5.3	(18)	62	(0.2)	0.8
12P	NI	1803	NI	NA	NI	NA	NI	32	NI	0.5
13P	NI	515	NI	NA	NI	NA	NI	15	NI	0.8
14A	529	529	18	27	0.9	1.4	13	21	0.7	1.1
15A	588	588	151	127	6.9	5.8	11	21	0.7	1.1
16P	NI	1426	NI	266	NI	5.0	NI	34	NI	0.7
19P	NI	418	NI	41	NI	2.7	NI	2	NI	0.1
TTL	20708	35340	799	2035			225	443		
ACRES	[475]	[811]								

(Continued)

Note: Values rounded to significant figures after all computations were completed. NI or ( ) indicates zone not part of channel condition. NA indicates no appreciable shoaling.

Table 4 (Concluded)

Zone	Area 1,000 sq ft Base	Plan	Total Shoaling* 1,000 cu yds/yr Base	Plan	ft/yr Base	Plan
1	1338	1688	5	6	0.1	0.1
2	1485	1839	NA	NA	NA	NA
3	1077	1641	18	21	0.4	0.3
4	1304	1722	24	31	0.5	0.5
5	1511	1997	5	11	0.1	0.1
6	965	2264	NA	NA	NA	NA
7	892	1489	5	2	0.2	NA
8	796	1580	7	3	0.2	0.1
9	594	848	8	4	0.4	0.1
10	661	1147	NA	NA	NA	NA
11	834	1221	19	12	0.6	0.3
12	710	710	20	16	0.7	0.6
13	718	718	19	22	0.7	0.8
14	666	666	21	32	0.9	1.3
15	661	661	90	144	3.7	5.9
16	1109	1109	166	235	4.0	5.7
17	1966	1966	238	278	3.3	3.8
18	2305	2305	188	304	2.4	3.6
19	NI	1646	(10)	177	(0.2)	2.9
20	NI	709	(11)	110	(0.4)	4.2
21	NI	2137	(92)	484	(1.2)	6.1
12P	NI	1803	NI	32	NI	0.5
13P	NI	515	NI	15	NI	0.8
14A	529	529	31	48	1.6	2.5
15A	588	588	162	148	7.4	6.8
16P	NI	1426	NI	300	NI	5.7
19P	NI	418	NI	43	NI	2.8
TTL	20708	35340	1023	2478		
ACRES	[475]	[811]				

* Summation of cohesive and noncohesive deposition.

APPENDIX A: THE TABS-2 SYSTEM

1. TABS-2 is a collection of generalized computer programs and utility codes integrated into a numerical modeling system for studying two-dimensional hydrodynamics, sedimentation, and transport problems in rivers, reservoirs, bays, and estuaries. A schematic representation of the system is shown in Figure A1. It can be used either as a stand-alone solution technique or as a step in the hybrid modeling approach. The basic concept is to calculate water-surface elevations, current patterns, sediment erosion, transport and deposition, the resulting bed surface elevations, and the feedback to hydraulics. Existing and proposed geometry can be analyzed to determine the impact on sedimentation of project designs and to determine the impact of project designs on salinity and on the stream system. The system is described in detail by Thomas and McAnally (1985).

2. The three basic components of the system are as follows:

   a. "A Two-Dimensional Model for Free Surface Flows," RMA-2V.

   b. "Sediment Transport in Unsteady 2-Dimensional Flows, Horizontal Plane," STUDH.

   c. "Two-Dimensional Finite Element Program for Water Quality," RMA-4.

3. RMA-2V is a finite element solution of the Reynolds form of the Navier-Stokes equations for turbulent flows. Friction is calculated with Manning's equation and eddy viscosity coefficients are used to define the turbulent losses. A velocity form of the basic equation is used with side boundaries treated as either slip or static. The model automatically recognizes dry elements and corrects the mesh accordingly. Boundary conditions may be water-surface elevations, velocities, or discharges and may occur inside the mesh as well as along the edges.

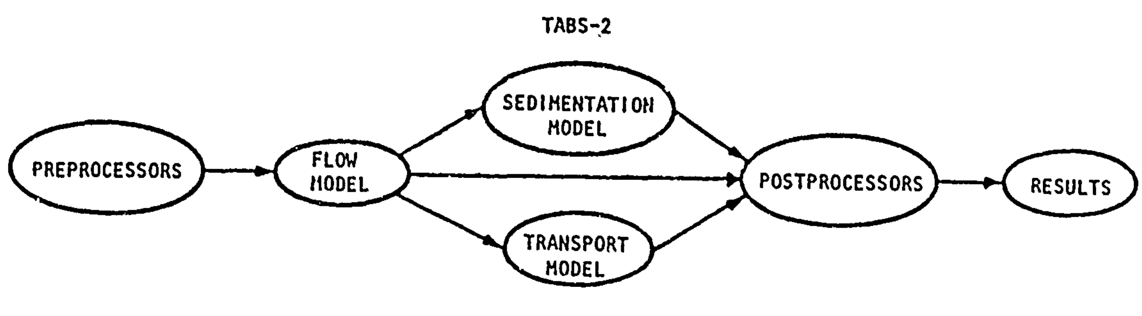


Figure A1. TABS-2 schematic

4. The sedimentation model, STUDH, solves the convection-diffusion equation with bed source terms. These terms are structured for either sand or cohesive sediments. The Ackers-White (1973) procedure is used to calculate a sediment transport potential for the sands from which the actual transport is calculated based on availability. Clay erosion is based on work by Partheniades (1962) and Ariathurai and the deposition of clay utilizes Krone's equations (Ariathurai, MacArthur, and Krone 1977). Deposited material forms layers, as shown in Figure A2, and bookkeeping allows up to 10 layers at each node for maintaining separate material types, deposit thickness, and age. The code uses the same mesh as RMA-2V.

5. Salinity calculations, RMA-4, are made with a form of the convective-diffusion equation which has general source-sink terms. Up to seven conservative substances or substances requiring a decay term can be routed. The code uses the same mesh as RMA-2V.

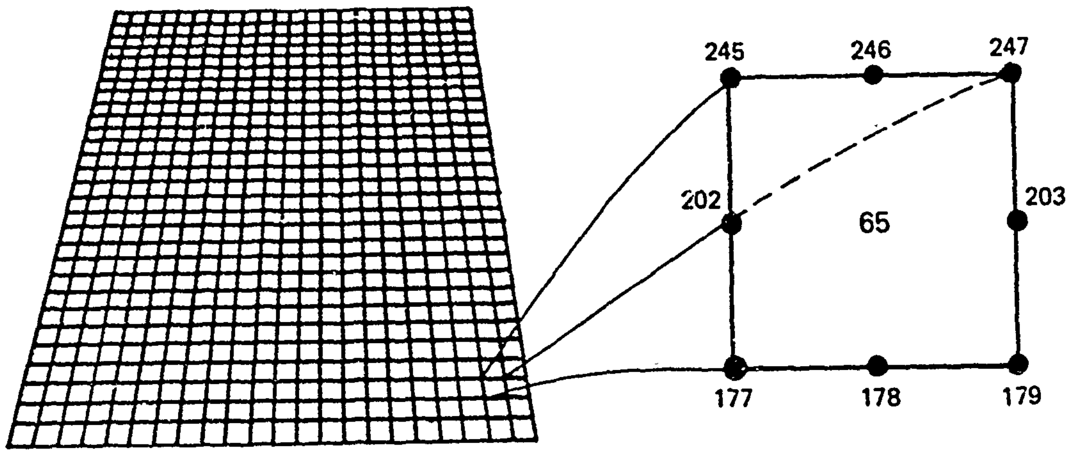
6. Each of these generalized computer codes can be used as a stand-alone program, but to facilitate the preparation of input data and to aid in analyzing results, a family of utility programs was developed for the following purposes:

- a. Digitizing
- b. Mesh generation
- c. Spatial data management
- d. Graphical output
- e. Output analysis
- f. File management
- g. Interfaces
- h. Job control language

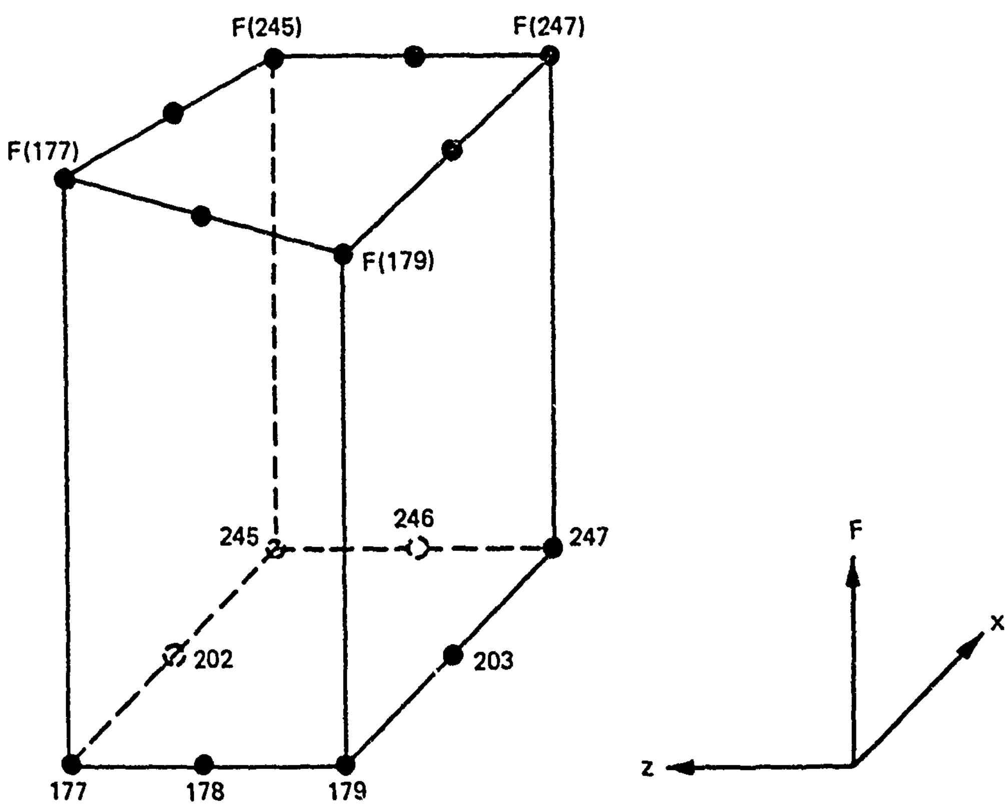
Finite Element Modeling

7. The TABS-2 numerical models used in this effort employ the finite element method to solve the governing equations. To help those who are unfamiliar with the method to better understand this report, a brief description of the method is given here.

8. The finite element method approximates a solution to equations by dividing the area of interest into smaller subareas, which are called elements. The dependent variables (e.g., water-surface elevations and sediment



a. Eight nodes define each element



b. Linear interpolation function

Figure A2. Two-dimensional finite element mesh concentrations) are approximated over each element by continuous functions which interpolate in terms of unknown point (node) values of the variables. An error, defined as the deviation of the approximation solution from the correct solution, is minimized. Then, when boundary conditions are imposed, a set of solvable simultaneous equations is created. The solution is continuous over the area of interest.

9. In one-dimensional problems, elements are line segments. In two-dimensional problems, the elements are polygons, usually either triangles or quadrilaterals. Nodes are located on the edges of elements and occasionally inside the elements. The interpolating functions may be linear or higher order polynomials. Figure A2 illustrates a quadrilateral element with eight nodes and a linear solution surface where F is the interpolating function.

10. Most water resource applications of the finite element method use the Galerkin method of weighted residuals to minimize error. In this method the residual, the total error between the approximate and correct solutions, is weighted by a function that is identical with the interpolating function and then minimized. Minimization results in a set of simultaneous equations in terms of nodal values of the dependent variable (e.g. water-surface elevations or sediment concentration). The time portion of time-dependent problems can be solved by the finite element method, but it is generally more efficient to express derivatives with respect to time in finite difference form.

The Hydrodynamic Model, RMA-2V

Applications

11. This program is designed for far-field problems in which vertical accelerations are negligible and the velocity vectors at a node generally point in the same directions over the entire depth of the water column at any instant of time. It expects a homogeneous fluid with a free surface. Both steady and unsteady state problems can be analyzed. A surface wind stress can be imposed.

12. The program has been applied to calculate flow distribution around islands; flow at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, at river junctions, and into and out of pumping plant channels; and general flow patterns in rivers, reservoirs, and estuaries.

Limitations

13. This program is not designed for near-field problems where flow-structure interactions (such as vortices, vibrations, or vertical accelerations) are of interest. Areas of vertically stratified flow are beyond this program's capability unless it is used in a hybrid modeling approach. It is two-dimensional in the horizontal plane, and zones where the bottom current is in a different direction from the surface current must be analyzed with considerable subjective judgement regarding long-term energy considerations. It is a free-surface calculation for subcritical flow problems.

Governing equations

14. The generalized computer program RMA-2V solves the depth-integrated equations of fluid mass and momentum conservation in two horizontal directions. The form of the solved equations is

$$h \frac{\partial u}{\partial t} + hu \frac{\partial u}{\partial x} + hv \frac{\partial u}{\partial y} - \frac{h}{\rho} \left(\epsilon_{xx} \frac{\partial^2 u}{\partial x^2} + \epsilon_{xy} \frac{\partial^2 u}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial x} + \frac{\partial h}{\partial x} \right)$$

$$+ \frac{gun^2}{\left(1.486h^{1/6}\right)^2} \left(u^2 + v^2\right)^{1/2} - \zeta V_a^2 \cos \psi - 2h\omega v \sin \phi = 0 \qquad \text{(A1)}$$

$$h \frac{\partial v}{\partial t} + hu \frac{\partial v}{\partial x} + hv \frac{\partial v}{\partial y} - \frac{h}{\rho} \left(\epsilon_{yx} \frac{\partial^2 v}{\partial x^2} + \epsilon_{yy} \frac{\partial^2 v}{\partial y^2} \right) + gh \left(\frac{\partial a}{\partial y} + \frac{\partial h}{\partial y} \right)$$

$$+ \frac{gvn^2}{\left(1.486h^{1/6}\right)^2} \left(u^2 + v^2\right)^{1/2} - \zeta V_a^2 \sin \psi + 2\omega hu \sin \phi = 0 \qquad \text{(A2)}$$

$$\frac{\partial h}{\partial t} + h \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + u \frac{\partial h}{\partial x} + v \frac{\partial h}{\partial y} = 0 \qquad \text{(A3)}$$

where

h = depth

u,v = velocities in the Cartesian directions

x,y,t = Cartesian coordinates and time

ρ = density

ϵ = eddy viscosity coefficient, for xx = normal direction on x-axis surface; yy = normal direction on y-axis surface; xy and yx = shear direction on each surface

g = acceleration due to gravity

a = elevation of bottom

n = Manning's n value

1.486 = conversion from SI (metric) to non-SI units

ζ = empirical wind shear coefficient

V_a = wind speed

ψ = wind direction

ω = rate of earth's angular rotation

ϕ = local latitude

15. Equations A1, A2, and A3 are solved by the finite element method using Galerkin weighted residuals. The elements may be either quadrilaterals or triangles and may have curved (parabolic) sides. The shape functions are quadratic for flow and linear for depth. Integration in space is performed by Gaussian integration. Derivatives in time are replaced by a nonlinear finite difference approximation. Variables are assumed to vary over each time interval in the form

$$f(t) = f(0) + at + bt^c \qquad t_0 \leq t < t \tag{A4}$$

which is differentiated with respect to time, and cast in finite difference form. Letters a , b , and c arc constants. It has been found by experiment that the best value for c is 1.5 (Norton and King 1977).

16. The solution is fully implicit and the set of simultaneous equations is solved by Newton-Raphson iteration. The computer code executes the solution by means of a front-type solver that assembles a portion of the matrix and solves it before assembling the next portion of the matrix. The front solver's efficiency is largely independent of bandwidth and thus does not require as much care in formation of the computational mesh as do traditional solvers.

17. The code RMA-2V is based on the earlier version RMA-2 (Norton and King 1977) but differs from it in several ways. It is formulated in terms of velocity (v) instead of unit discharge (vh), which improves some aspects of the code's behavior; it permits drying and wetting of areas within the grid;

and it permits specification of turbulent exchange coefficients in directions other than along the x- and z-axes. For a more complete description, see Appendix F of Thomas and McAnally (1985).

The Sediment Transport Model, STUDH

Applications

18. STUDH can be applied to clay and/or sand bed sediments where flow velocities can be considered two-dimensional (i.e., the speed and direction can be satisfactorily represented as a depth-averaged velocity). It is useful for both deposition and erosion studies and, to a limited extent, for stream width studies. The program treats two categories of sediment: noncohesive, which is referred to as sand here, and cohesive, which is referred to as clay.

Limitations

19. Both clay and sand may be analyzed, but the model considers a single, effective grain size for each and treats each separately. Fall velocity must be prescribed along with the water-surface elevations, x-velocity, y-velocity, diffusion coefficients, bed density, critical shear stresses for erosion, erosion rate constants, and critical shear stress for deposition.

20. Many applications cannot use long simulation periods because of their computation cost. Study areas should be made as small as possible to avoid an excessive number of elements when dynamic runs are contemplated yet must be large enough to permit proper posing of boundary conditions. The same computation time interval must be satisfactory for both the transverse and longitudinal flow directions.

21. The program does not compute water-surface elevations or velocities; therefore these data must be provided. For complicated geometries, the numerical model for hydrodynamic computations, RMA-2V, is used.

Governing equations

22. The generalized computer program STUDH solves the depth-integrated convection-dispersion equation in two horizontal dimensions for a single sediment constituent. For a more complete description, see Appendix G of Thomas and McAnally (1985). The form of the solved equation is

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + \alpha_1 C + \alpha_2 = 0 \qquad \text{(A5)}$$

where

C = concentration of sediment

u = depth-integrated velocity in x-direction

v = depth-integrated velocity in y-direction

D_x = dispersion coefficient in x-direction

D_y = dispersion coefficient in y-direction

α_1 = coefficient of concentration-dependent source/sink term

α_2 = coefficient of source/sink term

23. The source/sink terms in Equation A5 are computed in routines that treat the interaction of the flow and the bed. Separate sections of the code handle computations for clay bed and sand bed problems.

Sand transport

24. The source/sink terms are evaluated by first computing a potential sand transport capacity for the specified flow conditions, comparing that capacity with the amount of sand actually being transported, and then eroding from or depositing to the bed at a rate that would approach the equilibrium value after sufficient elapsed time.

25. The potential sand transport capacity in the model is computed by the method of Ackers and White (1973), which uses a transport power (work rate) approach. It has been shown to provide superior results for transport under steady-flow conditions (White, Milli, and Crabbe 1975) and for combined waves and currents (Swart 1976). Flume tests at the US Army Engineer Waterways Experiment Station have shown that the concept is valid for transport by estuarine currents.

26. The total load transport function of Ackers and White is based upon a dimensionless grain size

$$D_{gr} = D \left[\frac{g(s - 1)}{\nu^2}\right]^{1/3} \tag{A6}$$

where

D = sediment particle diameter

s = specific gravity of the sediment

ν = kinematic viscosity of the fluid

and a sediment mobility parameter

$$F_{gr} = \left[\frac{\tau^{n'}\tau'^{(1-n')}}{\rho g D(s-1)}\right]^{1/2} \tag{A7}$$

where

τ = total boundary shear stress

n' = a coefficient expressing the relative importance of bed-load and suspended-load transport, given in Equation A9

τ' = boundary surface shear stress

The surface shear stress is that part of the total shear stress which is due to the rough surface of the bed only, i.e., not including that part due to bed forms and geometry. It therefore corresponds to that shear stress that the flow would exert on a plane bed.

27. The total sediment transport is expressed as an effective concentration

$$G_p = C\left(\frac{F_{gr}}{A} - 1\right)^m \frac{sD}{h}\left(\frac{\rho}{\tau}U\right)^{n'} \tag{A8}$$

where U is the average flow speed, and for $1 < D_{gr} \leq 60$

$$n' = 1.00 - 0.56 \log D_{gr} \tag{A9}$$

$$A = \frac{0.23}{\sqrt{D_{gr}}} + 0.14 \tag{A10}$$

$$\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53 \tag{A11}$$

$$m = \frac{9.66}{D_{gr}} + 1.34 \tag{A12}$$

For $D_{gr} < 60$

$$n' = 0.00 \tag{A13}$$

$$A = 0.17 \tag{A14}$$

$$C = 0.025 \tag{A15}$$

$$m = 1.5 \tag{A16}$$

28. Equations A6-A16 result in a potential sediment concentration G_p. This value is the depth-averaged concentration of sediment that will occur if an equilibrium transport rate is reached with a nonlimited supply of sediment. The rate of sediment deposition (or erosion) is then computed as

$$R = \frac{G_p - C}{t_c} \tag{A17}$$

where

C = present sediment concentration

t_c = time constant

For deposition, the time constant is

$$t_c = \text{larger of} \begin{cases} \Delta t \\ \text{or} \\ \dfrac{C_d h}{V_s} \end{cases} \tag{A18}$$

and for erosion it is

$$t_c = \text{larger of} \begin{cases} \Delta t \\ \text{or} \\ \dfrac{C_e h}{U} \end{cases} \tag{A19}$$

where

Δt = computational time-step

C_d = response time coefficient for deposition

V_s = sediment settling velocity

C_e = response time coefficient for erosion

The sand bed has a specified initial thickness which limits the amount of erosion to that thickness.

Cohesive sediments transport

29. Cohesive sediments (usually clays and some silts) are considered to be depositional if the bed shear stress exerted by the flow is less than a critical value τ_d . When that value occurs, the deposition rate is given by Krone's (1962) equation

$$S = \begin{cases} -\dfrac{2V_s}{h} C \left(1 - \dfrac{\tau}{\tau_d}\right) \quad \text{for} \quad C < C_c & \text{(A20)} \\ \\ -\dfrac{2V_s}{hC_c^{4/3}} C^{5/3} \left(1 - \dfrac{\tau}{\tau_d}\right) \quad \text{for} \quad C > C_c & \text{(A21)} \end{cases}$$

where

S = source term

V_s = fall velocity of a sediment particle

h = flow depth

C = sediment concentration in water column

τ = bed shear stress

τ_d = critical shear stress for deposition

C_c = critical concentration = 300 mg/ℓ

30. If the bed shear stress is greater than the critical value for particle erosion τ_e , material is removed from the bed. The source term is then computed by Ariathurai's (Ariathurai, MacArthur, and Krone 1977) adaptation of Partheniades' (1962) findings:

$$S = \frac{P}{h} \left(\frac{\tau}{\tau_e} - 1\right) \quad \text{for } \tau > \tau_e \qquad \text{(A22)}$$

where P is the erosion rate constant, unless the shear stress is also greater than the critical value for mass erosion. When this value is exceeded, mass failure of a sediment layer occurs and

$$S = \frac{T_L P_L}{h\Delta t} \quad \text{for } \tau > \tau_s \qquad \text{(A23)}$$

where

T_L = thickness of the failed layer

P_L = density of the failed layer

Δt = time interval over which failure occurs

τ_s = bulk shear strength of the layer

31. The cohesive sediment bed consists of 1 to 10 layers, each with a distinct density and erosion resistance. The layers consolidate with overburden and time.

<u>Bed shear stress</u>

32. Bed shear stresses are calculated from the flow speed according to one of four optional equations: the smooth-wall log velocity profile or Manning equation for flows alone; and a smooth bed or rippled bed equation for combined currents and wind waves. Shear stresses are calculated using the shear velocity concept where

$$\tau_b = \rho u_*^2 \qquad \text{(A24)}$$

where

τ_b = bed shear stress

u_* = shear velocity

and the shear velocity is calculated by one of four methods:

<u>a</u>. Smooth-wall log velocity profiles

$$\frac{\bar{u}}{u_*} = 5.75 \log \left(3.32 \frac{u_* h}{\nu}\right) \qquad \text{(A25)}$$

which is applicable to the lower 15 percent of the boundary layer when

$$\frac{u_* h}{\nu} > 30$$

where $\bar{u}$ is the mean flow velocity (resultant of u and v components)

b. The Manning shear stress equation

$$u_* = \frac{(\bar{u}n)\sqrt{g}}{CME\ (h)^{1/6}} \qquad (A26)$$

where CME is a coefficient of 1 for SI (metric) units and 1.486 for non-SI units of measurement.

c. A Jonsson-type equation for surface shear stress (plane beds) caused by waves and currents

$$u_* = \sqrt{\frac{1}{2}\left(\frac{f_w u_{om} + f_c \bar{u}}{}\right)\left(\bar{u} + u_{om}\right)^2} \qquad (A27)$$

where

f_w = shear stress coefficient for waves

u_{om} = maximum orbital velocity of waves

f_c = shear stress coefficient for currents

d. A Bijker-type equation for total shear stress caused by waves and current

$$u_* = \sqrt{\frac{1}{2} f_c \bar{u}^2 + \frac{1}{4} f_w u_{om}^2} \qquad (A28)$$

Solution method

33. Equation A5 is solved by the finite element method using Galerkin weighted residuals. Like RMA-2V, which uses the same general solution technique, elements are quadrilateral and may have parabolic sides. Shape functions are quadratic. Integration in space is Gaussian. Time-stepping is performed by a Crank-Nicholson approach wi.h a weighting factor (θ) of 0.66.

A front-type solver similar to that in RMA-2V is used to solve the simultaneous equations.

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